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An investigation of patterned ground

AN INVESTIGATION OF PATTERNED GROUND

An Investigation of Patterned Ground

Frank H. Nicholson 1969

ABSTRACT

MEMORANDUM ON THE CIRCUMSTANCES OF THE STUDY

To accompany dissertation entitled "An Investigation of Patterned Ground".

The results, ideas and conclusions presented in this dissertation are the individual work of the writer. All ideas, and results taken from material published by other workers are fully acknowledged in the text. Naturally the three supervisors have given advice. Dr R.M.S.Perrin, the supervisor at the School of Agriculture, Cambridge University, was also concerned with the same field of research, though not working in collaboration. His results, ideas and conclusions were published after the work based upon Cambridge was completed, and are discussed in the text. Mr L.F.Curtis and Mr D.Ingle Smith, both of the Department of Geography, University of Bristol, who supervised the work during the later stages, did not directly participate in the research.

Signed. Frank H. Nicholson
Frank H.Nicholson.

Date. 6 Sept 1969

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ABSTRACT

This investigation began as a study of fossil patterned ground in East Anglia, but was broadened in scope when it became obvious that existing published reports of comparable active patterned ground only allowed very limited interpretation of the patterns of East Anglia. The final investigation included field observations on active patterns in Arctic North America and Europe, especially the Seward Peninsula, Alaska and Finnmark, Norway. Much of the evidence was visual and not easily expressed in a quantitative form. A large number of diagrams and plates are presented as an essential supplement to the inevitably subjective description. The review of literature on patterned ground was largely based upon the work of Washburn(1956), but information relevant to the mechanism of origin was drawn from a wide variety of sources.

The descriptive classification suggested by Washburn was reluctantly abandoned in the light of the field evidence, and a new synthesis of descriptive terms is proposed. When possible existing terms were used, taking care to avoid distorting existing definitions. The new classification is based upon surface form, grouping and marking. Proposed terms for form are 'equiform'(replacing the ambiguous terms 'circle', 'polygon' and 'net'), 'stripe', 'elongate'(intermediate between stripes and equiforms) and 'step'. The grouping of patterns is divided into 'isolate', 'contiguous' and 'grouped'(the latter for doubtful intermediate cases). The terms 'relief', 'stone' and 'vegetation', or combinations, are proposed for the description of pattern marking. The terms 'sorted' and 'non sorted' are rejected because of the contradictions arising from the dual descriptive and genetic use of these terms. An 'other variations' category is added to both form and marking descriptive categories to allow for occasional occurrences not covered by the proposed terms.

Permafrost, the heat flux in ground subjected to freezing temperatures, possible ways in which pressure in the ground is produced by freezing, frost susceptible materials, and movements in patterned ground are all discussed as major factors affecting patterns.

The field evidence does not differ markedly from the type of evidence produced by previous workers, though perhaps the size and number of excavations is notable. Air photographs were used extensively. Important observations included gradations between almost all forms, groupings and markings of patterns; clear evidence of circulatory movement in pattern sections; and elongated patterns apparently parallel to lines of drainage rather than parallel to the maximum slope.

Discussion of the field data includes the evaluation of evidence on the development and perpetuation of patterned ground once the pattern is established; direct and indirect evidence of mechanisms of movement; evidence of actual movements; the initiation of the pattern of patterned ground; the utility of patterned ground as a palaeoclimatic indicator; and the rate of pattern development. An important conclusion is that the pattern forming processes may all be incorporated into two models for pattern development - a radial movement model and a circulatory movement model, the former perhaps being a special modification of the latter. Additionally each of the three main field areas is treated independently for presentation of evidence and deductions. The fossil patterns of East Anglia are thought to indicate former continuous permafrost conditions. A major part of the concluding section is entitled "Towards a more rational understanding of patterned ground", which summarises many of the writers ideas.

A N   I N V E S T I G A T I O N   O F

P A T T E R N E D   G R O U N D

V O L U M E   I

BY FRANK H. NICHOLSON

Dissertation prepared for submission to the University of Bristol in fulfilment of the requirements of candidature for the degree of Doctor of Philosophy.

SEPTEMBER 1969

C O N T E N T S

V O L U M E I

MAPS IN POCKET

VOLUME II

ILLUSTRATIONS AND DIAGRAMS IN SUPPORT OF THE TEXT

INTRODUCTION

The initial plan of this study was firstly to define the distribution and form of the patterned ground in East Anglia, U.K. and secondly to study similar forms of patterned ground which are active and hence to interpret the origin and significance of the East Anglian patterns. During the course of the study many inadequacies of the present knowledge of patterned ground became obvious. This resulted in the emphasis of the study being shifted towards remedying some of the inadequacies and rather less work on the full interpretation of the patterns of East Anglia.

The work commenced with a study of the extremely widespread and exceptionally well preserved large patterns of East Anglia. The most comparable active pattern area revealed by a literature search was in the Seward Peninsula, Alaska, which was selected as the second major area of field study. The studies in Scandinavia were undertaken in an attempt to define the southward limit of activity of the large patterns seen in the Seward Peninsula, central Alaska, and north west Canada.

At the beginning of the study the system of classification devised by Washburn (1950, 1956) was used rigidly in the field work. The present writer was very reluctant to propose either a new classification or new theories of origin of patterns. Considerable differences of interpretation did, however, arise and hence the present study has involved a complete resynthesis of both the classification of patterned ground and ideas on the origin and development. The synthesis of Washburn is criticised in detail since this work is widely used and many attempts have been made to apply his ideas in patterned ground studies. This should not detract from the immense value of the digest produced by Washburn, which indeed gave inspiration for many ideas of the present study. The work of Troll (1944) and Hopkins and Sigafoos (1951) also should be specially mentioned as being of particular value in the following study.

To a large extent evidence has been presented separately from the deductions in order that the observations may be of value even if the deductions do not stand in the light of future observations. Since most of the evidence is either visual or can be presented visually particularly large numbers of plates and figures are presented with the same aim in view.

THE CLASSIFICATION OF PATTERNED GROUND

2.1 DEFINITION OF PATTERNED GROUND

The term patterned ground is used specifically for approximately regular, repetitive features in the regolith that are usually, though not exclusively, associated with frost action. This definition is in general agreement with the definition of patterned ground as used by Washburn (1956 pp 824-825 and references in support). Patterned ground can vary in size from a few centimetres to several hundred metres for each unit pattern. The term does not include artificial ground patterns, nor patterns resulting from biological activity alone nor very large ground patterns (such as seen in Plate 17). The definition according to Washburn (1956) would include gilgae (Costin 1955, Hallsworth, Robertson and Gibbons 1955) and possibly would be taken to include such features as mud crack patterns(Knechtel 1951 Flint 1957, West 1968). Most authors, however, seem to have applied the term exclusively to forms associated with frost action and use special justification when applying the term to forms not associated with frost action (Costin 1955).

2.2 THE WASHBURN DESCRIPTIVE CLASSIFICATION OF PATTERNED GROUND

A very large number of terms have been proposed for patterned ground forms. As pointed out by Washburn (1956) the same forms have been given different names and the same names have been applied to different forms. The classification proposed by Washburn (1950 and 1956) has been accepted by many authors (e.g. Gradwell 1957, Billings and Mooney 1959, Drew and Tedrow 1962, Williams 1964, Brown J. 1966). A number of previous classifications had been proposed (see Washburn 1956 P825 and references),and the ideas of Troll (1944) are particularly noteworthy. Washburn bases his classification on two main features which are thought to be readily recognised. Firstly the patterns are divided according to the form of the pattern appearing at the surface, for example polygons. The second feature used in the classification is "the presence or absence of obvious sorting between stones and fines" (Washburn 1956 p826). It should be especially noted that Washburn emphasises that his classification is descriptive not genetic. The resulting classification is set out below.

TABLE I

The Washburn Classification of Patterned Ground (1956 p 826)

Circles	Sorted (including debris islands) Nonsorted (including peat rings, tussock rings)
Nets	Sorted Nonsorted (including earth hummocks)
Polygons	Sorted Nonsorted (including frost crack polygons, ice wedge polygons, tussock-birch-heath polygons, desiccation polygons)

Steps	Sorted Nonsorted
Stripes	Sorted Nonsorted

Washburn points out at some length that "gradations in pattern and sorting" occur and quotes previous authors who have described gradations (Washburn 1956 p 826 and references). Washburn takes each class and describes it in turn, giving definition, description and examples. For the present study it is useful to separate the discussion of the surface form (circles, polygons, nets etc.) from the discussion of the characteristic marking of the surface form (sorting or lack of sorting).

A circle is defined by Washburn as "patterned ground whose mesh is dominantly circular .." (p 827 and p 829). Nets are defined as intermediate between circles and polygons. Polygons have a mesh that is dominantly polygonal. Similarly steps are defined as having a step-like form and stripes as having a striped pattern.

Circles are said by Washburn to develop singly or in groups, whereas polygons "apparently" do not develop singly. Thus the distinction between circles, nets and polygons is purely on their geometric shape and clearly not on their grouping.

Unfortunately this simple geometric classification is not easily applied in the field. Relatively few patterns are almost circular or almost polygonal. A notable example of a polygonal form is the ice wedge polygon. Other circular or polygonal patterns can undoubtedly be found. However, the majority of patterned ground forms are neither definite polygons nor circles. Thus a very large number of patterned ground forms should be termed nets. The situation is not improved by consideration of earth hummocks - specifically cited in Washburn's classification table. These would seem to have a mesh that is "dominantly circular" - yet they are included by Washburn as an example of the class of "nets".

There are considerable objections to the term "net", since a mesh of a net in the common usage can have a variety of forms, often fairly precise geometric shapes, and usually all of identical size. Minor confusion arises due to problems as to whether "net" is describing a single unit or a group of units of patterned ground. A much more fundamental difficulty arises when a pattern can be classified as either a circle or a polygon. Figure 1 illustrates an example of the problems that can arise.

A further objection arises in that an isolated unit or mesh of patterned ground is most commonly, and certainly ideally, circular. On the other hand the boundaries of individual units or meshes of contiguous patterns are almost certain to be polygonal (see figure 1d).

Washburn states "the unit component of patterned ground (except steps and stripes) - a circle, polygon or intermediate form - is here termed the mesh" (p 825). The definition of circles, nets and polygons was later given, in terms of the mesh. Thus the definition of the limits of a "mesh" is far from clear.

Another problem arises in that there are a large number of forms intermediate between circles (or nets?) and stripes. These are often the dominant form of pattern on a site, but remain intermediate and unclassified in the table above.

Washburn divides each of his geometric forms - circles, nets, polygons, stripes and steps - into sorted and nonsorted. This distinction is purely on surface features. A sorted circle is described as having "a sorted appearance due to a border of stones surrounding finer material" (p 827). The terms sorted and nonsorted are intended to be descriptive not genetic. Unfortunately the terms "sorted" and "nonsorted" immediately imply presence or absence of a sorting process. Sorting processes have been the subject of a voluminous literature (see Corte 1961 for a recent example). There is no doubt that sorting as a process is a notable feature of many forms of patterned ground, and often perhaps the most important process. However, there is no doubt that some patterns are not formed primarily by sorting processes. It is therefore clear that sorting is a genetic process and the terms "sorted" and "nonsorted" can rapidly assume a genetic significance, even though this was not originally intended by Washburn. Many writers following Washburn have assumed that sorted patterns are genetically different from nonsorted patterns, for example Flint (1957 p 201) states "Some patterns are created by the systematic segregation (sorting) of coarse particles from fine .. Others are nonsorted ..".

Sorting has been satisfactorily demonstrated in patterns that would be described by Washburn as "nonsorted" (Schmertmann and Taylor 1965). Field observations in the course of the present study indicated sorting in "nonsorted" patterns. Washburn in his 1956 paper refers to a number of hypotheses for sorted patterns which do not necessarily involve any sorting processes. Washburn personally supports two hypotheses for the development of sorted patterned ground without essential sorting processes (pp 844 and 847). Washburn refers to both sorting in the (presumably descriptive) classification sense and the genetic sense on the same page, but no attempt is made at distinction (for example p 847). Thus although Washburn intended the classification to be descriptive only, sorting and nonsorting are genetic terms. It seems that forms can be described as "nonsorted" when sorting processes are active and forms can be described as "sorted" when they involve no sorting processes.

Disagreement between workers on the East Anglian area illustrates the confusion that can arise through use of the term "sorted" as a "descriptive" term. In 1955 Watt reported "stone stripes in Breckland," recording the patterns at Thetford which are marked by lines of stones, vegetation and soil differences. The plates published by Watt clearly showed lines of stone concentrations. In 1964 Williams comments that the use of the term "stone" stripes was misleading. "To justify the title "stone" stripes it would be essential, according to common understanding, that the alternating bands be textural opposites, differentiated by size of material as fine and coarse zones. Furthermore, each stripe should be the complement of its neighbour so that the pair, if mixed together, would reconstitute the original texture of the material" (p 342). Apart from the fact that Williams has equated "stone" with "sorted" (as Washburn had intended in a descriptive sense), this is a clear example of the extension of the term to a fully genetic meaning. It seems that the type of confusion seen above is the inevitable result of the dual descriptive and genetic meanings of the term "sorted."

There is also some slight doubt as to the purely descriptive nature of the terms circle, net and polygon. When criticising mechanisms Washburn often refers to circles and polygons in a way that could suggest that there is a fundamental genetic difference. Certainly they are given a suggested genetic significance in Washburn's conclusions.

2.3 CLASSIFICATION OF PATTERNED GROUND ACCORDING TO TROLL 1944

Troll suggested a classification on a rather different basis. He suggested classifying patterned ground into two main groups. In the first group were placed "structure soils" (strukturboden) and "texture soils" (texturboden). Structure soils are approximately equivalent to the later Washburn class of sorted patterns. The texture soil group is partly equivalent to nonsorted patterns, but more limited, the main example being ice wedge polygons and allied features. The second group suggested by Troll consisted of "amorphous frost soils" such as "hummocky ground," "peat hummocks," "string bogs," icing mounds," "solifluction ridges," "garland soils" and "rock streams." "Hummocky ground," "garland soils" and "peat hummocks" are included as patterned ground by many authors (Elton 1927, Sharp 1942b, Washburn 1956, Billings and Mooney 1959, Rapp and Rudberg 1964). Solifluction ridges, rock streams and string bogs generally are not mentioned by other authors when referring to patterned ground. There seems little reason to exclude icing mounds (see Muller S.W.1947) or pingos (Muller F. 1959) from any classification of patterned ground, though again these are not often mentioned in connection with patterned ground (though see West 1968).

Another major division proposed by Troll is into diurnal and seasonal forms of frost features. No exact distinguishing criteria are given, though some inferences can be made from his extensive selection of examples. It seems that the width of diurnal forms can be up to 75 cm, though more commonly less. Seasonal patterned ground seems to be 1.5 m or more.

2.4 PROPOSALS FOR REVISED DESCRIPTIVE CATEGORIES OF PATTERNED GROUND

2.41 Justification for Proposing New Categories

The papers by Washburn (1950 and 1956) outline the very large variety of patterned ground descriptive terms and attempts at classifications. So many different terms have been proposed for forms of patterned ground that there has been considerable confusion in the past. Further additions to the terminology could easily add to the confusion. The Washburn classification has been widely acknowledged though not always applied fully (e.g. Svensson 1963, Watt, Perrin and West 1966). No one simple descriptive classification or set of descriptive terms is likely to be perfect in every case. Hence it could well be thought that major new proposals for descriptive terminology are unjustified unless there are fundamental defects in the Washburn Classification.

The present writer believes that such fundamental defects do exist. The main problems concerning the Washburn classification are:-

1. In the field there are major difficulties in making valid distinctions between circles, nets and polygons.
2. It is possible to find examples of patterned ground that could be classified as either polygons or circles, although these classes were presumably intended as exclusive.
3. There are very large numbers of occurrences of patterns with forms intermediate between circles (or nets or polygons) and stripes. These clearly do not belong to any of the aforementioned classes and thus have no place in the classification.
4. The terms sorted and nonsorted are intended as descriptive. However, the term has been used to describe a genetic process, before and after the Washburn classification was proposed, and by Washburn in the papers proposing the classification.

Criticisms that are less important individually, though significant when considered as a whole are:-

5. There are objections to the term net in view of the meanings of the word in common usage.
6. Isolate patterns are probably ideally circular. Contiguous patterns are probably ideally polygonal (see figure 1). However, in the original sense the identification of circles and polygons was intended to be independent of grouping.
7. The term mesh is defined by reference to circles, nets and polygons, which is not a specific definition since circles, nets and polygons are

defined by reference to the mesh.

8. The terms circles, nets and polygons are used by Washburn in such a way as to lead to suspicions that they are terms with a genetic as well as descriptive significance.

9. The use of the negatively defined class "nonsorted patterns" has caused misconceptions concerning patterned ground.

Comments 1 to 8 have already been discussed in the above outline of the classification of patterned ground by Washburn. Comment 9 perhaps needs clarification. Following the setting up of the negatively defined class "nonsorted patterns" there has been an increase in the trend for sorted patterns to be regarded as the most important and easiest explained forms of patterned ground. Sorted patterns are often described as a class completely apart, whereas all other forms of patterned ground (the "nonsorted class") are largely treated as an ill defined group of mysteries (ice wedge polygons being a notable exception to this trend). The treatment of patterned ground by Embleton and King in the book "Glacial and Periglacial Geomorphology" (1968) represents perhaps an extreme example of the results of this trend.

2.42 Statement of the New Proposals

The present writer intends to propose a revised set of descriptive categories for patterned ground. Where possible previously accepted terms will be used. Where there is no accepted term it is intended as far as possible to use terms which have not already been used in patterned ground studies. In this section discussion of these categories will be largely in relation to published work. However, since this classification is based upon both literature and field studies some reference to field observations will be made in anticipation of the presentation of the field results.

From literature and field studies the following descriptive criteria seem most useful:-

1. The form of the pattern (stripe, step, etc.)
2. The grouping of the patterns
3. The way in which the pattern is marked.

For further definition and comparison of patterns quantitative data are needed - particularly pattern size, slope of the land and particle sizes of the material involved. However, not enough data are available for the present writer to attempt to define descriptive categories based upon quantitative data, even if this were desirable.

TABLE II

Proposed Descriptive Categories of Patterned Ground

Description of form	- Equiform Elongate Stripe Step (Other)
Description of Grouping	- Isolate Grouped Contiguous
Description of pattern marking	- Relief (variations) Stone (") Vegetation (") (Other variations)

2.43 Definitions of the New Descriptive Categories

The term 'unit' is chosen by the present writer for the basic repetitive unit of the pattern. In the case of an isolated pattern the unit is the entire form. The limits of a unit of patterned ground are often difficult to define. For this reason the definitions of the descriptive words for the pattern form are in terms of the prominent surface markings of the unit, whether or not these mark the true 'limits' of the unit. Suggestions for deciding the limits for measurement are given in Section 2.45.

The terms 'essentially' and 'markedly' as used below are deliberately not precisely defined. Until further data are available the definitions of what are 'essential' and 'marked' characteristics of a pattern form must depend on the individual judgement of the particular field worker.

CATEGORIES OF PATTERN FORM

EQUIFORM.* Equiforms are patterns in which the length of the maximum axis of the main marking of the pattern is not essentially greater than the minimum axis. Alternatively an equiform can be defined as a form which has a vertical axis of more than two fold symmetry. In looser terms this means patterns in which the units are not markedly elongated. (The term equiform is intended to include the previous descriptive categories 'circle', 'net' and 'polygon').

ELONGATE. Elongates are patterns with marked elongation of the units, but not indefinite elongation. Elongates are distinguished from equiforms by their essential elongation. They are distinguished from stripes in that the division into units in the direction of elongation is an essential feature. In the following section (2.44) some suggestions are given on the problem of distinguishing between very long elongates and stripes.

Footnote.* The word 'equiform' is believed to be a new word which would be geologically, geometrically and etymologically acceptable.

STRIPES. Stripes are linear patterns in which any interruptions of the linear features are not an essential part of the repetitive pattern. Previous to this thesis the term stripe has been applied by the majority of authors only to forms with the long axis oriented downslope. The present writer would prefer not to limit the term in this way. However, in view of the accepted usage the present writer suggests that special note should be made when the term stripe is not used for forms oriented in a general downslope direction. It should be noted that the words 'general downslope direction' are used rather than 'perpendicular to the contours'. The present writer is firmly opposed to a definition which implies orientation exactly at right angles to the contours, because of field observations.

STEPS. Steps are most ~~easiest~~ easily defined as patterns with a marked step form. A possible definition in more precise terms might be that a step must have a regular form with a quasi horizontal element plus a notable asymmetry with respect to the vertical plane.

It should be noted that whilst the definitions of equiform, elongate and stripe are mutually exclusive categories, the step form definition does not exclude an equiform, elongate or even stripe form in plan. Hence it may sometimes happen that the plan form and relief asymmetry are of equal weight in describing the surface pattern. In these cases it may be necessary to use two terms i.e. equiform steps, elongate steps or stripeform steps. Intermediate forms between the above categories have been recorded.

OTHER SURFACE FORMS. Other distinctive forms of patterned ground are possible. Sometimes a definite pattern of similar sized units but with irregular outline, can be seen both on the ground and on air photographs. Perhaps the string bogs of Troll (1944) should be included in this general group. Ringridge lakes (Svensson 1964a p 105 and below Section 6.6) may also belong to this group. Possibly the definition of steps should be enlarged to include garlands (Sharp 1942b), or possibly they should be included in this category.

CATEGORIES OF PATTERN GROUPING

ISOLATE patterns are patterns that are widely spaced and appear rarely, if ever, to impinge upon one another.

GROUPED patterns are patterns which are grouped together but not apparently forming a contiguous pattern covering the whole of an area. Grouped patterns often appear to impinge upon one another in part and form a semi regular repetitive pattern. The term 'grouped' is primarily designated to cover problematic occurrences in the field which appear to be neither isolate nor contiguous (see figure 2).

CONTIGUOUS patterns have units that appear to all impinge upon one another so that an entire area is covered. They usually, but not necessarily, form a very regular repetitive pattern.

CATEGORIES OF PATTERN MARKING

Patterns are distinguished by variations of some feature of the site. The main feature that varies and hence marks the pattern is used for the descriptive term. Minor variations of other features are ignored.

RELIEF VARIATIONS.

Patterns are often marked mainly by relief and sometimes no other variation may be easily discernible. Most commonly the 'centre' of the pattern is raised. Depressed centre features have been recorded and also more complex relief patterns (see figure 19). Patterns marked mainly by cracks or fractures can be considered to belong to this class if the relief expression of the cracks is the dominant feature marking the pattern.

STONE VARIATIONS

Variations of stones marking the pattern have received much attention in the past. The category of stone variations is intended to include both patterns marked by areas of different sizes of stones and patterns which are marked by areas of concentrations of stones contrasted to areas of relatively stone free material (fines, mud, soil etc.). The term 'stone' avoids the genetic implications of the term 'sorted' and it is hoped that 'stone' will replace 'sorted' for descriptive purposes.

VEGETATION VARIATIONS

There are a number of different types of vegetation variations that can mark the pattern. The variations may be variations of plant species, or plant density or growth form or growth vigour. This term is intended to include patterns marked by areas that have plants and areas that do not.

OTHER VARIATIONS

Variations of other features marking the patterns are possible, though probably not common. For example in some cases soil colour variations may be the main variation marking the pattern (see Plate 86).

Frequently combinations of relief, stone and vegetation variations occur. For instance vegetation patterns may also show relief variations and stone patterns also commonly show variations of relief. Most commonly, however, variations of one factor are mainly responsible for making the pattern visible. If two factors are both prominent then these terms can be used in combination, with a hyphen, e.g. relief-vegetation stripes. Variations of relief, stones and vegetation are not uncommonly found on one pattern, but the present writer has never seen an occurrence where all three could be said to be major features of the same pattern. Probably occasional relief-stone-vegetation patterns will be reported in the future.

2.44 Discussion of the Revised Descriptive Categories

The categories have been carefully designed to minimise cutting across accepted terminology.

Discussion of Categories of Pattern Form

In the revised categories there are three major new proposals. These are the proposals for the new terms equiform and elongate, and the revision of ideas on the orientation of stripes.

The term equiform is intended to provide a general term for circles, polygons and similar but less easily described forms. The term equiform is also intended to remove the absolute necessity for subjective subdivision in difficult cases. The term equiform may well counteract a tendency to regard circles and polygons as the main and commonest forms and to regard other forms as less common or less easily explained. The introduction of the term equiform will not cut across existing terminology, though probably the term net could be allowed to fall into disuse.

Some of the criticisms of the terms circles, polygons and nets as used by Washburn have been given above. In the field there is considerable difficulty in classifying equiform patterns into the three relevant Washburn classes. The subjective distinction between say polygons and nets seems to be very variable from one author to another - for instance compare the "nets" shown in figure 15, p 125 Johnson & Billings 1962 with the "polygons" shown in figure 2 , p 18 Billings and Mooney 1959. As pointed out by Washburn (1956), other authors have used the terms "polygon" and "circle" interchangeably (e.g. Elton 1927). Certainly some authors have used the term "polygon" with an extremely broad definition so that it is hardly distinguishable from the definition of "equiform" above (Taber 1929, Paterson 1951). The definition of the term nets is not enhanced by the earlier usage of the word by Troll (1944) to include, amongst other things "ice-wedge nets".

When discussing the origin of patterned ground Washburn frequently criticises particular hypotheses in such a way as to imply a genetic difference between circles and polygons (e.g. see Washburn 1956 pp 842 and 845). It seems in the majority of cases that Washburn's use of "polygons" and "circles" in this context could be best interpreted by substituting "Contiguous (equiforms)"and "isolate (equiforms)". The points at issue concerned whether or not the particular hypothesis explained patterns that did or did not interact with other patterns at the borders. It is difficult to reconcile this use of "circles" and "polygons" with the initial descriptions of the grouping of circles and polygons, which imply that the definitions of these terms are independent of grouping (as stated in section 2.2). The suggestion that Washburn believed that there are genetic differences between circles and polygons is further reinforced by his concluding section. He suggests that nets are formed by combination processes whereas circles and polygons are formed by end members. It seems unlikely to the present writer that a pattern is easier to interpret because it is easier to describe in geometrical terms.

In summary there seems to be some confusion between different authors as to the definition of polygons. Further there is difficulty in distinguishing between the three Washburn classes. The terms circles, polygons and nets may have been given more genetic significance than they should have. There seems to have been some need for a general term for "circles, nets and polygons" before the work of the present writer.

If patterns are clearly circular or clearly polygonal then this fact is worth noting and the patterns could obviously be described as circles or polygons. Circle and polygon would be regarded as particular shapes of equiform, which might or might not have any genetic difference from equiforms in general. The term equiform is not intended to replace the terms circle and polygon, but to provide a general category of which these special shapes would form a part.

The term elongate is proposed simply as a descriptive term for a form of pattern found to be common in the field. Many authors have commented on the existence of forms intermediate between equiforms and stripes (Troll 1944, Washburn 1947, Hopkins and Sigafoos 1951, Williams 1964). Williams, describing the fossil patterns of East Anglia, U.K., was forced to very considerably modify his description of stripes to cover large numbers of intermediate forms between stripes and "polygons". Hopkins and Sigafoos when describing vegetation patterns on the Seward Peninsula, Alaska, refer to "nets" becoming elongate on slopes (p 88) and also to "elongate polygons" (p 92). A considerable number of occurrences of forms with elongation are clearly neither stripes nor equiforms. Plates 4 and 21 show examples of elongates.

A major problem arises in defining the limits of the term elongate. In the definition above 'essential' elongation divides elongates from polygons. The decision as to what is essential must lie with the observer. When describing individual pattern units there is usually no problem. The decision as to whether or not a group of patterns are to be called elongates needs more consideration. Sometimes a small, but consistent, elongation is seen in all the units and the units and the overall area of patterning would be termed elongates. In other cases a few units may be found with more marked elongation than in the previous example, but scattered amongst a majority of units with no elongation. In this latter case the patterned area as a whole would probably be termed equiform. In the field, or on air photos, this problem is not very serious and only a small percentage of pattern areas give difficulty. Perhaps a long axis 1.5 times the length of the short axis is the lower limit of elongates. However, this figure is a tentative generalisation that is certainly not always applicable. It is possible that individual units might have elongation ratios of 2:1

before the area of patterns appears essentially elongate. Alternatively an elongation ratio of only 1.25:1 may appear to be an essential elongation.

The division between elongates and stripes is made according to whether or not there are essential divisions along the direction of elongation. Clearly stripes are not of infinite length. Many patterns with long linear forms show definite divisions which are widely spaced but seem to be an essential part of the pattern. Other long linear forms are seen which do not have essential divisions (Plates 78, 89 and 98). In the field, and when using air photos, an appreciable number of sites give considerable difficulty when dividing forms which might or might not be considered to have essential divisions. A decision as to a definite elongation ratio to divide elongates and stripes does not seem to solve the problem. Occasionally, when the elongation ratio exceeds approximately 8:1 any divisions are so irregular that they can be considered as non essential features. In other cases forms with an elongation ratio of 20:1 or greater seem to have essential divisions and to have a definite elongate, rather than stripe appearance.

In summary the term elongate is proposed to fill a need which appeared during the field and air photograph work. The division between elongates and equiforms is easily recognised, though on many sites intermediate zones between equiforms and elongates are present (see Plate 82). The division between elongates and stripes is much less easily decided. The distinction seems to be a valid one since clear examples of very long elongates can be found and also clear examples of stripes. Since the most problematic cases seem to be generally where there is a continuous series from stripes to elongates (and often also to equiforms) the problem is mainly one of description and should not seriously affect interpretation.

<u>In order to avoid confusion the present writer suggests that elongates with an elongation ratio greater than 10-15:1 should always be qualified 'long' elongates</u>. Probably many workers will attempt to define their own limits for 'long', 'short', and occasionally 'medium' elongates in terms of elongation ratio. In this case there will be no confusion, providing these limits are clearly stated. Unfortunately the pattern areas where the greatest difficulty occurs - the very long elongates - are the most time consuming to measure in the field.

The category stripes is largely in accord with past usage and descriptions. The <u>revision of ideas on the orientation of stripes</u> does however involve new principles, though not entirely without precedent. Washburn (1956) proposed that one part of the definition of stripe should be "oriented down the steepest available slope" (p 836).

Previously Troll (1944) recorded stripes not aligned downslope in the Drakensburg of South Africa. Black and Berg (1963) recorded stripes in Antarctica which were not aligned downslope. The present writer has also recorded examples of stripes that are not aligned exactly downslope.

The definition of <u>the term step</u> as given above is in accordance with previous definitions of the term. However the present writer suggests that provisions are made concerning orientation in a similar way to those for stripe above. Examples are recorded below of steps that do not necessarily have their steepest faces exactly on the downslope side. This may not exactly accord to the inferred usage by some authors, but this provision does not seem to violate previous formal definitions.

<u>Discussion of Categories of Pattern Grouping</u>

Different types of grouping are a feature of patterned ground. There is little doubt that isolate, contiguous and intermediate forms of patterned ground exist (e.g. see Hopkins and Sigafoos 1951). The use of 'circle' and 'polygon' by Washburn in an attempt to overcome this problem has already been mentioned above. Thus there seems to be a need for terms to describe patterned ground grouping. 'Isolate' and 'contiguous' are proposed, with 'grouped' for intermediate cases. An example of contiguous patterns which do not occur isolate is ice wedge polygons. An example of isolate patterns that do not occur contiguous is pingos. The main difficulty is to devise definitions of isolate and contiguous that are useful in field description. In part this task is impossible since a final decision on the extent to which patterns 'are contiguous', 'impinge upon one another' or are interacting can only be made after detailed investigation. The definitions given above are intended to be based on appearance alone so that descriptions can be made during field reconnaissance or during examination of good quality air photos. If pattern units described as grouped later proved on detailed investigation to be interacting it would still be useful to describe patterns as 'grouped in surface appearance'. It is inevitable that the decision as to whether or not a unit impinges on its neighbours will depend on the judgement of the individual worker. It is suggested that in critical cases patterns are described as 'closely grouped' rather than contiguous if there is a real doubt.

<u>Discussion of the Categories of Pattern Marking</u>

The main justification for the choice of the new terms for the categories of pattern marking is to be found in the field data presented in this thesis. The reasons for rejection of the two Washburn classes 'sorted' and 'nonsorted' have been given above. Many authors have referred to relief variations of patterned ground. Frequently authors have reported 'hummocks', which must be solely or dominantly marked by relief (Sharp 1942b, Troll 1944, Smith 1961). The proposal that relief should be used as a major category of pattern marking does not seem to have been made previously. The term 'stone patterns' is long established (e.g. Huxley and Odell 1924, Hawkes 1924, May 1936, Paterson 1940, Lundqvist 1949). The term vegetation patterns is also not new. The term was used by Hopkins and Sigafoos in the title of their 1951 paper "Frost Action and Vegetation Patterns on Seward Peninsula, Alaska". Although all these terms have already been used in connection with patterned ground this seems to be the first time that these three descriptive terms have been used in this way for categories of pattern marking, but this usage does not contradict previous usage. The fourth very small category of variations of other features is included for the sake of completeness. For instance a pattern could be marked by a silt centre surrounded by a sand margin, without stones, relief or vegetation. This could be covered by substituting 'textural variations' for 'stone variations', but would inevitably lead to confusion with the German and Scandinavian usages of 'structure' and 'texture' soils. It is likely that occasional candidates for this 'other variations' category will be reported from time to time.

In concluding the discussion on the proposals for revised descriptive categories two points cannot be overemphasised. The first is that these are descriptive categories intended for use in the field and for the reporting of results. The second point is that many gradational forms exist. There are gradations between all the categories in any group and many gradations between different combinations are possible. Striking examples seen during the present study included on one site gradations from relief-vegetation equiforms to stone equiforms and to stone-vegetation stripes. On another site gradations were observed from isolate vegetation steps via a number of stages to contiguous vegetation stripes.

2.45 The Limits of a Pattern Unit for Measurement

The limits of an individual unit are often far from obvious when making field observations. It is, however, necessary to make definite decisions in order to record measurements. For isolate patterns the only limits that can be taken are the limits of the pattern marking, which may not be at all clear and may not represent the limits of the processes forming the unit. For contiguous patterns the unit size should be measured from midway between adjacent patterns. In part this advice is not too useful since the decision as to whether or not patterns are contiguous will depend upon the decision as to what is the limit of the pattern unit. Unfortunately the vital decision as to whether or not patterns are described as contiguous must depend on the individual field worker. During the present study when some units in an area of patterns did not appear to be fully contiguous, measurements were taken on those patterns which looked as though they were contiguous. When measuring (contiguous) stripes more accurate measurements can be obtained by measuring a whole series cumulatively. Whilst it is often difficult to measure every pattern chosen at random, few sites are without some patterns that cannot be measured with confidence. This does carry with it the attendant danger of biasing the sample towards those patterns that for some reason or other are well marked. During the work in East Anglia there were some sites where it appeared that measuring only the very best marked patterns would have given a larger figure than the average pattern size. However, by making measurements as described above the figures recorded in this thesis are probably representative in the vast majority of cases.

2.5 THE CLASSIFICATION OF PATTERNED GROUND ORIGIN ACCORDING TO WASHBURN (1956)

Washburn summarised a large number of suggested mechanisms of origin of patterned ground in a series of hypotheses. He summarised each hypothesis and then reviewed the criticisms of each hypothesis and added criticisms and modifications of his own. It is notable that in most cases he is classifying according to the mechanisms proposed rather than according to the results of these mechanisms (e.g. he puts together contraction hypotheses rather than hypotheses explaining ice wedge polygons). The classification of mechanisms of origin is summarised below.

2.51 Hypotheses based on Expansion due to Freezing

Ejection of stones from fines due to multigelation. A whole variety of mechanisms are reviewed, all of which involve multiple freezing (multigelation), which causes the ejection of stones from fines. A digest of some of these mechanisms can be found in section 3.56.

Mass heaving. Washburn seems to include two distinct types of hypothesis under this single heading. Firstly an explanation of patterned ground assuming an initial uneven layer of fines below coarser material. The fines are thought to expand more than the coarser material and hence force their way to the surface, drawing and sucking more fines from below. Secondly an explanation of patterned ground involving regular deformation of the ground by expansion.

Local differential heaving. Irregularities of snow, plant cover or other factors are thought to cause different intensities of heaving, leading to the development of patterned ground.

Cryostatic movement. The pressure caused by the active layer freezing from the surface downwards towards the permafrost table is thought to develop patterned ground. Cryostatic is "formally defined as an adjective describing freezing induced hydrostatic phenomena" (Washburn 1956 p 842). Differences in the rate of downfreezing are postulated (as in local differential heaving), which would lead to the down-freezing front joining the permafrost table earlier in some places than in others. This would cause great pressure to develop in the areas left unfrozen, which is thought to result in the squeezing about of the unfrozen material. Washburn repeats the suggestion made by Troll (1944) that depth of thaw and of sorting action may control the size of patterns.

Circulation due to ice thrusting. Freezing is thought to move material upwards in the pattern centres and outwards across the surface of the patterns. Then by poorly understood means the freezing also causes downward movement at the borders and inwards movement at depth.

Frost wedging. Frost action upon bedrock weaknesses is thought to form certain types of patterned ground, which clearly must reflect the bed-rock weaknesses.

Expansion due to swelling of colloids. This mechanism, proposed for gilgae, is considered in relation to patterned ground formed in cold regions. It is rejected largely because colloids are generally only present in very small quantity in cold regions.

2.52 Weathering Hypotheses

Hypotheses that patterned ground is produced by differential weathering of the original material. Both vertical and horizontal differences produced by weathering have been proposed by different authors.

2.53 Contraction Hypotheses

Contraction due to drying. Hypotheses for the development of patterned ground forms due to this cause are based upon either drying due to evaporation or drying due to moisture being drawn off during freezing. The former process is thought to account for the initial pattern of many smaller forms of patterned ground.

Contraction due to low temperatures. Due to very low temperatures frozen ground is thought to contract, resulting in tensional cracks. This hypothesis is now widely accepted for the formation of ice wedge polygons, but its importance to the development of other forms of patterned ground is still in doubt.

Contraction due to thawing. The basis of this mechanism is that if ground expands during freezing then a contraction is to be expected on thawing. For this to produce patterned ground it must be assumed that this contraction is in three dimensions, not just vertically. (Certain hypotheses reviewed under the heading of ejection of stones by multi-gelation also rely in part upon three dimensional contraction during thawing).

2.54 Convection Hypotheses

Convection caused by temperature differences has been proposed as a mechanism for the origin of patterned ground. Convection due to density differences caused by moisture differences has also been proposed.

A modified hypothesis based upon moisture differences causing movement, but not necessarily in a convectional pattern, is proposed by Washburn.

2.55 Hypotheses based on differential thawing and eluviation

Fines nearest to stones will thaw first due to differences of thermal conductivity, hence giving preferential opportunity for the washing away of fines near to stones. The process is thought to result in islands of fines surrounded by stones when conditions are favourable.

2.56 Artesian hypotheses

The hydrostatic pressure of artesian water is thought to dome up the surface and hence develop patterns. (Since the only convincing widespread origin of artesian water in cold regions is that due to water trapped by the downfreezing active layer, this could perhaps be thought of as a modified cryostatic hypothesis).

2.57 RillworK hypothesis

Some authors have proposed that parallel rills could develop stripes by eluviation of the fines.

2.58 Solifluction Hypothesis

Washburn reports many workers as having suggested a downslope orientation of the patterned ground phenomena as due to a number of downslope movements. "Solifluction is essential to all these explanations, which can therefore be conveniently designated the solifluction hypothesis of origin of sorted and nonsorted stripes on slopes, as distinct from sorted and nonsorted patterns on essentially horizontal surfaces" (p 858). Washburn uses solifluction in the original sense proposed by Andersson (1906) i.e. solifluction is the slow flowing of saturated masses of waste on slopes. (The present writer does not agree that "solifluction" - especially in this strict sense - does summarise fairly the range of types of movement that Washburn mentions.)

Washburn concludes from his extensive study of the literature that patterned ground is multigenetic. This conclusion is in agreement with a number of earlier writers.

Washburn suggests that many frameworks of polygonal patterns are determined by contraction cracking, either due to drying or due to low temperatures. Many circular patterns are thought by Washburn to be explained by either local differential heaving or cryostatic movement. He believes sorting is mainly due to multigelation and eluviation. He thinks solifluction is of major significance in the development of patterned ground on slopes.

Washburn goes on to suggest that four of these processes may perhaps be considered as end members of a "continuous system". He suggests the end members perhaps explain some circles and polygons, some nets being formed by combinations of processes (p 859).

Further conclusions are that both circulation due to ice thrusting and convection due to temperature differences can be ignored.

Hypotheses thought to be valid under special circumstances are the frost wedging, weathering, artesian pressure and rillwork hypotheses.

The main deficiencies of the Washburn 1956 paper are probably inevitable in view of the volume of material to be covered. Firstly the discussion of many primary processes, particularly the actual processes of frost heaving, are neglected. Secondly the discussion in relation to specific examples is necessarily limited in such a comprehensive paper.

REVIEW OF SOME PROCESSES AND FACTORS AFFECTING PATTERNED GROUND

The review of suggested origins of patterned ground by Washburn (1950 and 1956) is the most important published work on this topic. However, this work is a review of the hypotheses of formation of patterned ground, rather than a study of the processes involved. Many authors have commented upon the large number of different hypotheses for the formation of patterned ground. In this selected review the present writer intends to concentrate mainly upon basic processes and factors which probably affect patterned ground, rather than reviewing large numbers of compound hypotheses put forward to explain individual sites.

3.1 PERMAFROST

Permafrost is the first factor to be considered because the presence of permafrost has very marked effects on freezing processes. However, permafrost is definitely not essential to the formation of all types of patterned ground. The systematic study of permafrost began earliest in the U.S.S.R. (see Nikiforoff 1928). The first major English language publication was in 1943 by Muller (revised 1947), though American miners and others had been dealing with permafrost at a much earlier date (for example see Moffit 1905).

Permafrost or permanently frozen ground is defined by Muller (1947) as "a thickness of soil or other surficial deposit or even of bedrock, at a variable depth beneath the surface of the earth in which a temperature below freezing has existed continuously for a long time (from two to tens of thousands of years)." (p 219). The frozen ground commonly contains large and small masses of ice in many forms, often making up a very high percentage of the permafrost (Sumgin et al 1940, Muller 1947, Hussey and Michelson 1966). The time that the freezing condition needs to be present before it can be called permafrost, and the effects of frozen ground (?permafrost) remaining a few years only are still subject to some debate (see especially Sumgin et al 1940 and Brown R. J. E. 1966).

Permafrost regions are usually classified into three zones - continuous, discontinuous and sporadic. According to Sumgin et al (1940) continuous permafrost has temperatures below $-15^{\circ}C$ at depth 10 to 15 m. Discontinuous permafrost* has temperatures between -5 and $-15^{\circ}C$ at the same depth. Sporadic permafrost has temperatures above $-1.5^{\circ}C$ at depth 10 to 15 m. Black (1950, 1954) suggests mean annual temperatures for the various zones are below $-5^{\circ}C$ for continuous permafrost and above $-1^{\circ}C$ for sporadic permafrost, though these figures are by no means universally accepted (e.g. see Highway Research

Footnote*: Muller and Sumgin do not use the term 'discontinuous permafrost' but this term is now generally accepted - see Black 1950, 1954, Ferrians 1965.

Board 1955, Brown 1960, Pewe 1963, Stearns 1966). Permafrost may be on the wane in many areas (Ray 1951) but has been proved to be actively forming in some areas of North America (Ray 1951, Hopkins, Karlstrom et al 1955). Typical permafrost distributions can be seen on the "Permafrost Map of Alaska", Map 1 in the pocket.

There is a layer above the permafrost that thaws each summer and refreezes the following winter. This is called the 'active layer' because it is the zone of most heaving and the top of the permafrost is the maximum limit of plant root penetration. The active layer is deepest towards the southern limits of arctic permafrost, where it can be several metres deep, and shallowest in the extreme north where it is usually a few tens of centimetres deep and may be only a few centimetres deep. In some regions where fossil permafrost is present at depth the freezing in the 'active layer' may not join the permafrost layer in winter but this situation can be ignored for the purposes of the present study. The active layer represents the limit of patterned ground formation except in the case of ice wedge polygons and hence is of much more interest in the present study than the actual permafrost. The depth of the active layer can vary considerably in one area (see especially Brown J. 1966). The depth of active layer varies with soil type, vegetation, moisture conditions and other factors, some of the reasons for this will be discussed in the following section.

The permafrost seems to act in a number of roles in the formation of patterned ground. It acts as a solid base for the development of cryostatic pressure (see section 2.51). The permafrost restricts drainage - a major causal factor in the presence of extensive bogs in regions of very low rainfall. Permafrost can act as a store of cold which causes freezing from below in winter, as well as from above (see section 3.2). Permafrost may also act in other ways.

The <u>permafrost table</u> is "a more or less irregular surface which represents the upper limit of the permafrost" (Muller 1947 p 219). In the present study the permafrost table in all cases also represents the base of the active layer and hence the limit of depth of summer thaw. The <u>frost table</u> is the upper limit of frozen ground at any time e.g. after a few weeks of thaw. The frost table can be at any level in the active layer, depending on the time being referred to, and should not be confused with the permafrost table.

3.2 THE HEAT FLUX IN GROUND SUBJECTED TO FREEZING TEMPERATURES

The heat flux in ground subjected to freezing does not seem to be radically different from the heat flux in soils generally. The best general account and discussion of the heat flux in soils is given by Geiger (1965).

The factors controlling heat gains or losses at the ground surface are the nature of the surface, the speed of conduction of heat downwards, insolation, air temperature, and sometimes other meteorological factors such as precipitation and wind. The presence or absence of insulating layers of vegetation or snow alter surface rates of heat exchange. Insolation absorbed will vary with the albedo of the surface. The amount of outgoing radiation from the surface will depend mainly upon the nature of the surface and its temperature.

Conduction of heat upwards or downwards in the ground depends mainly upon the thermal conductivity of the ground. The rate of heat movement will also depend upon the temperature gradient. The thermal conductivity of 'ground' is variable, mainly depending upon the thermal conductivity of the particles, the contact between adjacent particles and the moisture content. The thermal conductivity of clay is twice that of sand (Geiger 1965) and the thermal conductivity of dry peat is extremely low (Muller 1947). Further values for thermal conductivities are given in Table III (p 32). Moisture acts in several roles. Sometimes the main action of the moisture is to provide a good contact between particles of high thermal conductivity. The moisture may be the main conducting medium - for instance in wet peat.

Sometimes heat is transported through the soil by running water. In many tundra soils the saturated nature of the ground and poor drainage prevents this. When, however, it occurs it seems to be a very important mechanism and many major local changes of permafrost conditions are due to changes of drainage conditions (e.g. Sumgin, Geniev and Chekotillo 1939, Hopkins, Karlstrom et al 1955). In some cases it may be that the change in moisture conditions is responsible for the variations of the heat flux rather than the transport of heat by the movement of water. Muller (1947) states that appreciable changes of the thermal regime can be achieved by artificially draining before the ground is frozen and flooding during the thaw season. Measurements at Point Barrow showed consistent variations between the depth of thaw in soils with different drainage characteristics. Better drained soils showed greater summer thaw and greater diurnal variations near the surface (Drew, Tedrow, Shanks and Koranda 1958).

The specific heat of the material will affect the actual temperature change for a given heat gain or loss. Water is again very important in notably altering the specific heat of ground.

When freezing temperatures are penetrating the ground then certain other factors need to be taken into account. If water is present it has two notable effects on the penetration of freezing temperatures. The thermal conductivity of ice is very different from the thermal conductivity of water and the thermal conductivity of the ground can be altered radically on freezing. In particular the thermal conductivity of ice is 3.7 times that of water near to freezing point. Heat conduction by saturated peat is dependent almost entirely on the moisture content. Hence the thermal conductivity of saturated peat also increases about 3.7 times on freezing. Thus saturated peat will allow much faster heat losses when frozen than it will allow heat gains when unfrozen. The presence of peat tends to produce lower average ground temperatures. The thermal conductivity of wet clay increases 1.7 times and the thermal conductivity of wet sand increases 3 times on freezing (Muller 1947). Moisture also affects the heat flux due to the change of state on passing the freezing temperature. Latent heat is released when water freezes and the penetration of freezing temperatures into the ground is slowed by this release of heat. Similarly when ice thaws heat is needed for the change of state and hence the penetration of thawing temperatures is slowed. This phenomenon of the arresting of the penetration of freezing or thawing temperatures by the change of state of water is called the 'zero curtain effect' (Muller 1947, following Sumgin et al 1940).

Hopkins and Sigafoos (1951, p 62) give examples of differential penetration of freezing temperatures during a cold period. "... the ground froze to a depth of more than 6 inches in bare soil, 3 to 5 inches in living sphagnum, 1 to 4 inches in wet peat, and 0 to 2 inches in dry peat and turf." At the same time 1 inch of ice was present on puddles. These figures illustrate a number of the above points. The present writer found frozen ground shallowest under living sphagnum after a month of thaw in the same general area as the work by Hopkins and Sigafoos. This is a demonstration of an example when the conditions that favoured fast penetration of freezing temperatures did not favour fast penetration of thawing temperatures. Both peat and vegetation tend to encourage a lower temperature regime in the ground (Muller 1947, Viereck 1965). Peat encourages a negative heat budget because its thermal conductivity when frozen is much greater than its thermal conductivity when unfrozen. The effects of vegetation are discussed in section 7.2.3.

Observations of the heat flux in a permafrost area by Annersten (1966) are by no means straightforward. Possibly the complexity of his data reflects the large number of observations or the complexity of the area where he worked. He concludes that vegetation is not an important factor affecting soil temperatures in the area of Schefferville. He thinks that snow cover is the most important factor. The action of snow as an insulating layer is well known.

Snow slows the penetration of both freezing and thawing temperatures (Smith 1961, Geiger 1965). Bay, Wunnecke and Hays (1952) working outside the permafrost zones concluded that frost penetration is controlled by vegetation cover as well as by depth of snow and air temperature. Janson (1964), in a quantitative study of frost penetration emphasises the importance of particle size and especially moisture content. Taber (1943) concluded that depth of thaw depended upon exposure, materials, vegetation and peat insulating layers.

The general ground temperature at depth is normally approximately the same as the mean annual temperature. Roughly speaking, when the mean annual temperature is zero degrees Centigrade then permafrost is present (though see also section 3.1). If the general ground temperature is well below zero degrees Centigrade then freezing temperatures can penetrate unfrozen ground not only from the surface but also from below. Observations by Black (1951a) and Schmertmann and Taylor (1965) demonstrate penetration of freezing temperatures from below. There has been some doubt as to whether or not 'upfreezing' occurs, and how important it is (e.g. see Washburn p 842 and references). Rather than referring to the penetration of freezing temperatures perhaps it is more correct to refer to heat being conducted from the unfrozen active layer both upwards and downwards. This is the same as the appropriate part of the normal heat flux in soils. The annual positive heat wave continues travelling downwards after the surface has begun cooling. Frequently the time of maximum temperatures near the limit of penetration of the annual wave coincides with the time of minimum temperatures at the surface.

It seems important to remember that most of these factors are not independent variables. For example vegetation cover affects the thermal flux, the thermal flux will affect the vegetation (Raup 1951, Benninghoff 1952, Sigafoos and Hopkins 1952, Viereck 1965). The presence of frozen ground strongly affects the drainage and the ground temperatures will affect evaporation. The effects of moisture conditions on ground temperatures have been outlined above.

In summary it seems that there are a number of factors that affect the heat flux in ground subjected to freezing. The importance of moisture content and thermal conductivity of soils are well known. The variations of thermal conductivity with changes from frozen to unfrozen state are known to affect permafrost conditions. The importance of this fact in relation to the formation of patterned ground does not seem to have been considered. The zero curtain effect has been widely appreciated, though perhaps not always considered in studies of patterned ground. Surface covers (snow and vegetation) have been shown to be important variables affecting frost penetration, though perhaps not in all circumstances. There has been some disagreement on the importance of penetration of freezing temperatures upwards from the permafrost table as well as downwards from the surface. The present writer has shown that this is not inconsistent with the accepted normal annual heat flux in soils. Further discussion of this point will be presented after the reporting of the field evidence.

3.3 POSSIBLE WAYS IN WHICH FREEZING PRODUCES PRESSURE IN THE GROUND

The majority of reports on patterned ground refer to frost heave or pressures produced by freezing. Relatively few authors discuss the precise way in which these pressures develop. Washburn (1956) refers to mass heaving, local differential heaving, multigelation, cryostatic pressures and many other "processes" involving pressure produced by freezing, but only occasionally refers briefly to how these pressures might develop. This is not due to any neglect by Washburn, but rather to the relatively small attention paid to this aspect by most of the authors he reviewed.

All authors agree that in natural materials moisture must be present to allow expansion pressures to develop on freezing.

3.31 Pressure produced by the increase in volume of water on freezing

The increase of volume of water on freezing is a well known effect and is undoubtedly capable of producing pressure. In order that the increase of volume should develop significant pressure the freezing water must be confined. It is necessary to consider how freezing water bodies might be confined and produce pressure in association with patterned ground. There seem to be two main ways suggested in the literature. Freezing water in the ground can be confined between frozen ground at the surface and permafrost below (e.g. see Ahlmann 1936, Muller 1947, Hopkins and Sigafoos 1951). Similarly water can be trapped between frozen ground at the surface and solid rock below (Troll 1944). In either case, however, although the freezing water is confined the pressures may not develop entirely, or even primarily, because of the volume increase when water freezes.

3.32 Pressure produced by the Segregation of Ice

If ice crystals form in the ground and have a continuing supply of moisture they will continue to grow whilst the temperature and other conditions remain favourable. This leads to the development of segregated ice which can develop pressures independent of the expansion of water on freezing. The ice crystals usually grow perpendicular to the freezing front and develop forces acting perpendicular to the freezing front rather than general pressures, though general pressure may result from these perpendicular acting forces (Taber 1929, 1930, Paterson 1940, Corte 1966).

The importance of ice crystals growing perpendicular to freezing fronts and therefore developing considerable force without confinement has perhaps been neglected in studies of simple rock fracture as a component of frost weathering.

Growth of Segregations of ice supplied with water drawn by the crystalisation processes through capillaries ('Taber ice')

Extensive studies of frost heaving caused by the segregation of ice supplied by water drawn through capillaries were published by Taber in 1929 and 1930. In experiments simulating freezing from the surface of the ground downwards Taber demonstrated the development of pressure producing upward heaving greater than 60% of the depth of freezing. The following outline is based upon Taber's work.

As freezing temperatures penetrate moist ground ice crystals form. It seems that the cohesive forces of water in contact with ice crystals are sufficient to draw further water to the ice crystals when the molecules of water adhering to the ice crystals become fixed. If the material in which the ice crystal is growing has suitable pore sizes then water can be drawn upwards from below. The migration of water to the ice crystal (bringing with it heat), and the release of latent heat as the water freezes, both tend to halt the penetration of freezing temperatures at the depth of the ice/water interface. This gives a static freezing front or zero curtain effect. The form of the crystals developed during the experiments by Taber was most commonly lenses of ice parallel or sub-parallel to the surface, though other forms were produced.

Taber demonstrated the development of lenses and heaving with liquids that decrease in volume as they freeze. Thus he clearly demonstrated that the heaving pressure produced by the ice lenses is independent of the increase of volume of water on freezing. It is most convenient to refer to segregation of ice by this mechanism as 'Taber ice segregation'.

Taber found that the main factors affecting the segregation of ice by this mechanism were the size and percentage of voids, the size and shape of particles, the available water, the rate of cooling, the surface load of resistance to heave and the direction of cooling. He also found that if the moisture supply was under pressure then the amount of heave was greater.

In a suitable deposit a lens of almost indefinite thickness can develop if there is a balance between the rate of moisture supply and the removal of heat. If the rate of supply of heat by the moisture is less than the rate of conduction away of heat then the freezing front will advance. Other ice lenses can then develop at lower levels in a similar way, often producing ice lenses at semi regular intervals. The appearance of the ice lenses suggests the descriptive term 'ice gneiss' (Taber 1943, Bryan 1946). Since the original study by Taber there have been a number of elaborations of the theory of Taber ice development (recent examples are Takagi 1963, Palmer 1967).

Taber ice has been reported at many patterned ground sites (e.g. Caine 1963, Andrews 1963, Schmertmann and Taylor 1965, Chambers 1967). Other authors have reported evidence that could be interpreted as indicating the action of Taber ice. Nikiforoff (1928) reports 'lamellae' observed in pattern sections. The 'stratification' of Ahlmann (1936) might be interpreted as produced by Taber ice.

Needle ice (Troll 1944) has been reported in association with many patterned ground sites, particularly the smaller forms (e.g. Troll 1944, Gradwell 1957, Andrews 1963). Fujita et al (1937) demonstrated that needle ice is simply Taber ice forming at the surface of the ground.

Taber (1943) attributed almost all heaving in patterned ground to 'Taber ice'. Whilst there is overwhelming evidence for the importance of Taber ice at many localities this latter view seems to oversimplify the mechanisms of frost heaving in patterned ground. Hoekstra, Chamberlane and Frate (1965) demonstrated that even when Taber ice is present some of the heaving pressure is not developed by Taber ice segregations. Some water is not taken into the Taber ice lenses and is trapped, unfrozen, after the freezing front has passed. When this water later freezes and expands extra pressure is produced. In the experiments of Hoekstra et al this extra pressure was measured as 10% of the total pressure.

Growth of segregations of ice with water supplied to the growing ice crystals by external forces

Frost heaving has been reported in materials with pores too large to allow water to be drawn up against gravity (Krynine and Judd 1957, Corte 1961). It is desirable to consider mechanisms which might produce ice segretations in such materials.

If the freezing front is advancing from below then ice crystals can be supplied by moisture moving by gravity alone, hence producing ice segregations and possibly heaving.

The active layer freezes from the surface downwards, and regardless of whether or not there is simultaneous upfreezing this can lead to hydrostatic pressure. (Leffingwell 1915, 1919, Nikiforoff 1928, Tolstkhin 1940). This pressure could possibly move moisture in the ground to supply ice crystals at either an upfreezing or a downfreezing front. Hence this mechanism might produce ice segregations and possible pressure.

Where there is suitable surface relief an artesian (semi-artesian or sub-artesian) flow can occur between the downfreezing surface layers and the permafrost (Muller 1947). This could supply growing ice crystals at both the upfreezing and downfreezing fronts. It would be difficult to distinguish between these suggested mechanisms of water supply by field tests. Undoubtedly all the above mechanisms could work in combination.

It is difficult to deduce the exact forms of ice segregation that would be produced by these processes. Probably some would resemble Taber ice (ice gneiss form), and some forms would be irregular. Hydrolaccoliths and pingos are undoubtedly examples of ground ice segregations growing by water supplied by hydrostatic pressure and often probably semi-artesian pressure (F. Muller 1959). These processes could also occur in soils which do have pore sizes suitable for the growth of Taber ice segregations.

3.33 Pressure due to Expansion of Frozen Ground after contraction due to very low Temperatures

Basically this is the mechanism proposed by Leffingwell (1915) for the formation of ice wedges, and now accepted by most authors (e.g. Black 1952, Lachenbruch 1962, Péwé 1966). The mechanism proposed is that after the active layer freezes the temperatures become so low that the frozen ground contracts and causes deep cracking. These cracks become filled with ice due to water entering during the early part of the thaw, when temperatures at depth are still very low. When the temperatures of the frozen ground rise it expands again. Since the cracks are already filled the expansion causes pressures and sometimes heaving.

When considered in relation to patterned ground in general the above paragraph needs qualification. The amount of contraction in a single cold season is relatively small. The development of a noticeable amount of heave seems to depend on the continued development of ice in the contraction cracks over many seasons (Leffingwell 1915, Black 1952). The ice development is cumulative in the case of ice wedge polygons because they are developed in permanently frozen ground (Black 1952, Hopkins, Karlstrom et al 1955, Pewe 1966). Most other forms of patterned ground are active layer features and therefore the ice from each winter thaws during the following warm season. Hence cumulative build up of heaving by the contraction mechanism is impossible in most forms of patterned ground. Additionally it is unlikely that pressures are caused by this mechanism in shallow forms of patterned ground because the upper part of the frozen ground will not be at very low temperatures when the first thaw occurs. Hence the cracks will be virtually closed before there is any likelihood of them becoming 'fixed' open. Thus the contraction due to low temperatures is likely to produce significant heaving pressure in the permafrost but not in the active layer.

Although contraction may not produce heaving in the active layer this does not rule out the possibility advocated by Washburn (1956) that the weaknesses developed by contraction cracking may help to determine the initial outlines of the patterns.

3.4 FROST SUSCEPTIBLE MATERIALS

The importance of Taber ice segregations in many cases of frost heave is accepted by all authors. In climates where frost action is likely, engineering practice attempts to avoid conditions likely to favour the development of Taber ice segregations. The development of Taber ice depends upon the porosity being such that moisture can be drawn through the capillaries. Materials with pores of suitable size for the development of Taber ice are described as 'frost susceptible'.

The original work of Taber (1929, 1930) showed that clays were very susceptible to the development of 'Taber ice' and clean sands not susceptible at all. The largest particles affected by frost heave according to Taber were .002 or possible .003 mm. This grain size limit is considerably lower than the limit accepted by later workers. Authors following Taber, particularly engineers, defined frost susceptibility in terms of percentage finer than a certain size (e.g. Casagrande 1932). The limit of frost susceptibility was taken as 3% finer than 0.02 mm. Beskow (1930) devised frost susceptibility boundaries taking into account the total particle size distribution instead of 'fines' alone - for example a material consisting largely of coarse sand would need a higher percentage of 'fines' to allow Taber ice to develop than a material consisting largely of fine sand. Haley and Kaplar (1951) demonstrated that the character of the fines is important. If the 'fines' are clay then material with less than 3% fines will heave. From field observations, Corte (1962) suggested that the upper limit of 'fines' for the purposes of defining frost susceptibility should be taken as 0.07 mm rather than 0.02 mm. Hoekstra, et al (1965) carried out experiments on frost heaving by development of Taber ice, part of their work being a confirmation of the conclusions of Haley and Kaplar. Hoekstra et al emphasise the importance of testing materials to determine frost susceptibility, rather than deducing whether or not materials are frost susceptible from assumed porosities based on particle size analyses. The suggestion arises that capillarity of materials might be determined by frost heave tests, rather than frost heaving being deduced from capillarities.

Whilst Taber ice is undoubtedly very important, particularly in its effect on man made structures, examples of frost heaving in 'non frost susceptible' materials have been recorded. Corte (1966) demonstrated both by laboratory and field experiments that frost heaving can take place in 'non frost susceptible' materials if they are saturated.

Presumably the development of heaving in non frost susceptible materials is produced by growth of segregations of ice with water supplied to the growing ice crystals by external forces as described in the previous section. Perhaps the term 'non frost susceptible' should be qualified so that it means 'not susceptible to the development of Taber ice'.

3.5 MOVEMENTS IN PATTERNED GROUND

All forms of patterned ground seem to be due to movement of materials, most commonly, but not exclusively, by frost action.

3.51 Movement by Simple Freezing Dilation and subsequent Thawing

In many cases, on horizontal ground, freezing produces upward dilation of the ground. On thawing the ground will tend to return to its former position, so that there is no net movement of the material. Even if there are differences in the amount of dilation from place to place this will not necessarily produce net movements. Vegetation patterns could be produced by differential dilation alone, without net movement of materials, simply by the varying stability of the rooting conditions for the plants (Hopkins and Sigafoos 1951, Benninghoff 1952).

Some authors have postulated that the ground expands in three dimensions and hence produces buckling of the ground surface rather than uplift alone (e.g. Elton 1927). Whether or not this would give a net movement on thawing is not at all clear. However, such a movement would give opportunity for other processes to act differentially.

On sloping ground dilation is most commonly perpendicular to the surface, whereas on thawing the particles will tend to fall back vertically. This produces a net downslope movement as is well known in connection with soil creep (for example see basic texts such as Sparks 1960). In connection with patterned ground this downslope movement consequent solely upon freezing and thawing has perhaps been neglected. Inevitably an area of ground that dilates more will have a greater downslope movement than adjoining ground that dilates less. There will also tend to be downslope movements on the pattern microrelief.

Similarly any movements perpendicular to a non horizontal freezing front, whether or not the ground is horizontal, are almost certain to give a net movement after thawing.

3.52 Movement of Material due to Migration of Particles at the Freezing Front

Corte (1966) demonstrated that particles will migrate along with a freezing front of ice, if the freezing rate is suitable. Fine particles move more than coarse particles. The particle sizes that move vary with the freezing rate and other factors, including particle shape. Obviously this process will result in sorting and can produce other differential movements. A secondary effect of sorting demonstrated by Corte is that the sorted materials will occupy a larger volume and hence could cause dilation of the ground. This applies equally to sorting by any other process. The recent work on these processes by Corte represents an important new contribution to our understanding of patterned ground.

3.53 Movements due to the Differential Formation of Taber Ice and Other Ice Segregations

Taber (1929) demonstrated that different materials develop differing amounts of Taber ice under the same moisture and freezing conditions. This causes differential movement of some materials in relation to others. On thawing some, or even all, of this movement will be reversed. However, it seems that often part of the differential movement is permanent, especially if the movement is not vertical or if some materials move non vertically into the voids produced when the ice thaws. Since needle ice is simply Taber ice at the surface, movements due to needle ice are included here.

It seems that micro faulting contemporaneous with the development of ice lenses under load (see Taber 1929 p 453) also causes differential movement of materials. This possibility does not seem to have been considered in relation to patterned ground.

Probably all of the above applies equally to ice segregations other than Taber ice, but these have not been investigated in such detail (though see Corte 1966).

3.54 Movement of Unfrozen Material by Freezing Pressures

If a uniform freezing pressure is developed the unfrozen materials can only be compressed. If the freezing pressure varies then the movement of unfrozen material is possible from an area of high to lower pressure. Gorodkov (1930) recorded a complete lack of field evidence for catastrophic movement of unfrozen material to the surface. The idea of differential pressure on the unfrozen material producing small movements rather than sudden 'injections' seems more acceptable to the present writer.

3.55 Other Movements contributing to the Formation of Patterned Ground

Various hypotheses of patterned ground formation have proposed eluviation of fines as a primary or subsidiary mechanism of movement (e.g. Washburn 1956). Micro mass movement, either on a general or single pattern slope, has also been proposed. The two main mechanisms of micro mass movement seem to be the flow of saturated fines and the rolling downslope of larger particles (Williams 1964, Chambers 1967).

'Solifluction' in connection with patterned ground has been hypothesised. Reservations concerning 'solifluction' and patterned ground will be discussed in section 7.10.0. Dessication cracking undoubtedly produces limited movements in some cases (Washburn 1956). Movements can be produced by mechanical sorting of unfrozen materials dist bed by freezing movements, especially upfreezing (Corte 1966).

Postulated movements that seem to be much less acceptable are fines adhering together during thawing (Hogbom 1914), suction (produced in an unknown way, movement by convection currents (Low 1925) and wind action (Lewis 1952).

Movements can be produced by pressures of expansion following contraction, but as explained above these movements are probably only important in ice wedge polygons.

3.56 The Uplift and other movements of Stones

The uplift of stones can be considered as a special case of movement, though probably too many authors have been mesmerised by sorting processes. The movement of stones can be considered simply as one case of differential migration of varying sized particles at a freezing front. Another possibility is the differential formation of Taber ice. A further possibility depends upon the fact that heave decreases downwards in many cases. During downfreezing the stone is fixed to the freezing layer by its top and is uplifted the same distance as the finer materials at the top of the stone. During thawing the stone remains fixed until it thaws at the bottom and hence it only sinks back as much as the fines at the base. This mechanism corresponds well with the observations of Chambers (1967) on Signy Island. Yet another possibility is that material slumps under the stone as the ground thaws though this is not completely distinct from the previous postulates. Beskow (1930, 1935) Vilborg (1955), have described in detail variations on these last two possibilities. It seems likely that the ideas of Beskow (1930, 1935) should be partially re-evaluated in the light of the results of Corte.

Thus there are a number of possible ways in which stones may be uplifted, though in most cases these 'mechanisms,' if they are completely distinctive, probably act in combination.

Whilst the above considers the vertical movement of stones there is little doubt that similar processes act with inclined downfreezing fronts to produce movements of stones mainly towards the direction of heat loss.

TABLE III Thermal conductivities (cal/m/h/°C).

After Bykov and Kapterev, given in Muller 1947, p 55.

Water	0.47–0.58	Ice (varying density)	1.8–2.05
Air	0.02–0.022	Clean Gravel (3–8 cms)	0.29–0.32
Granite	2.7–3.5	Fine quartz sand	0.05
'Dry dirt'	0.12	Fine river sand	0.26–0.28
'Moist dirt'	0.58	Limestone (varying density)	0.58–1.14
Peat	0.03–0.04	Quartz (axis variations)	6.12–11.52

STUDIES IN ALASKA

4.1 GENERAL INTRODUCTION

The studies on patterned ground in the British Isles preceded the work in Alaska. The Seward Peninsula, Alaska, was selected for studies of active patterned ground because of the published description of vegetation patterns of this area by Hopkins and Sigafoos (1951). These were the only published descriptions that seemed to closely resemble the patterned ground of East Anglia. This area is described here first because it is useful to consider first an arctic area where the patterns seem to be active before considering an area of fossil patterned ground.

Most of Alaska away from the Pacific Ocean coast is underlain by permafrost (see map 1). Intensive studies of permafrost in Alaska have been undertaken (see especially Hopkins, Karlstrom et al 1955). However, not all authors are agreed as to the exact boundaries of permafrost zones though to some extent variations are due to varying aims of the researcher (e.g. compare figure 3 by Pewe 1966 with map 1). When compared to the glaciations of North West Europe it seems surprising that Alaska was by no means completely ice covered during the glacial periods (see map 2).

The first major serious studies of Alaska date from the Gold Rush days at the turn of the century. In this period the Seward Peninsula was lucky in being one of the early gold mining areas and hence was mapped and geological surveys made earlier than many other areas (Moffit 1905, 1913, Collier et al 1908, Smith 1910). These early reports include reports on permafrost conditions in the area and useful summaries of the thick layers of unconsolidated deposits exposed in many gold mining sections which are not now available for study. In more recent years the Seward Peninsula has been singled out for special study for several reasons. The accident of being near to Russia promoted research in the area immediately after World War II (e.g. Hopkins 1949, 1963, Hopkins and Sigafoos 1951). The defence interest in this area has waned but interest has been maintained by the problems of the Bering Land Bridge (Hopkins and Giddings 1953, Hopkins 1959b), and also by the presence of a particularly good series of Pleistocene deposits in the area (Hopkins 1959a, Hopkins and Benninghoff 1953, Hopkins, MacNeil and Leopold 1960, Colinvaux 1964). Due largely to the efforts of the Alaskan Geological Survey and to D.M. Hopkins in particular, the last episodes of geological history of this area are perhaps better known than those in ~~any~~ other part of Alaska.

For the present study all the detailed work in Alaska was carried out in the Seward Peninsula, with scattered brief observations in other parts of Alaska. The work was naturally limited by transport and in particular by the road system leading out of Nome. The main work was limited to the area between Nome and the centre of the Seward Peninsula.

Three glaciations have been detected in the Seward Peninsula by Hopkins (1963), the Iron Creek Glaciation, the Nome River Glaciation and the Salmon Lake Glaciation. The Nome River glaciation is correlated with the Illinoian Glaciation and the Salmon Lake Glaciation is correlated with the Wisconsin Glaciation. Evidence from the Nome coastal area suggests that since the end of the Wisconsin Glaciation the area has warmed considerably and then cooled again (Hopkins et al 1960). The climatic data of the area are summarised in figure 22 and table X (section 8.22). A brief account is included at the end of Appendix A.

4.2 DESCRIPTION OF THE PATTERNED GROUND

To avoid unnecessary repetition individual sites will only be described when generalisations are not justified. The plates plus explanatory notes give a fair impression of a representative selection of the actual sites. Detailed site data are given in Appendix A.

It is notable that very few examples of 'perfect' patterned ground were found. Large forms of patterned ground are best seen from the air, to get a good perspective view. On the ground only the most obvious sites are easily recognised. Even when searching for patterns it is possible to walk over patterned areas without recognising them. Small patterns are much easier to recognise because it is easy to get a perspective view of a number of patterns (compare plates 31 and 47). It is important to note that the plates in this thesis represent the best patterns seen. Perhaps much of the literature is misleading in giving the impression that patterned ground is obvious. In the experience of the present writer the majority of patterned sites are very easily overlooked.

4.2.1 Variations of the Surface Pattern

Once the problem of recognition has been overcome the main problem is the bewildering variety of pattern forms and markings. It is tempting to regard each site, or even part of a site, as unique. Much of this difficulty is exaggerated by the many gradations from one pattern expression to another.

The problems of the description of the surface pattern have already been described in section 2.4 and the proposals for modified descriptive terms - equiform, elongate, stripes, steps, were made to overcome field problems. It should be remembered that many gradations are found. In the case of the large forms of patterned ground only equiforms were found on slopes less than 1.5 degrees. Elongates were by far the most common form, and were found on slopes between 0.5 and 15 degrees (see Appendix D Table D6). It was particularly notable that elongates are aligned one to another up and down slope and yet do not represent stripes that have been broken up. At site X34 (plate 38) the appearance was a whole host of small frost scars (bare soil areas) arranged in overall stripes. It is always difficult to explain how one cell of the pattern 'communicates' to another where to locate itself, but it seems that a special explanation is needed for this observation. Stripes are found much less commonly, all on slopes within the range for elongates, and sometimes near the lower limit of the range. Near the section at site F2, Coffee Creek, well marked elongates were not elongated exactly down-slope, but were angled approximately 10 degrees away from the line of maximum slope. Steps were not common in the area, though they were found in combination with other forms of patterns (see Plates 5 and 11). Other sizes of patterned ground were observed in such small numbers that it is not possible to give useful generalisations on the shape and relationships to slope.

It was notable that superimposed on some ice wedge polygon areas (perhaps 30 to 60 m diameter) there were a number of large patterns (circa 7-9 m diameter). The central areas of the large patterns were frequently divided into areas about 1.5 to 2 m diameter. On these areas micro patterns diameter 12 to 20 cm were often present (see Plates 1, 2 and 4). Thus there is commonly a hierarchy of patterns, despite the fact that ice wedge polygons are features of the permafrost and the other patterns are features of the active layer.

4.2.2 Variations of Vegetation on the Patterns

The vegetation found on the large forms of patterned ground varied from zero (freshly frost disturbed mineral soil as seen in Plate 1) to birch or willow up to 1 m tall (as seen in plate 8). The only general rule is that the vegetation on the centres of the patterns is either less well developed or more hardy than the vegetation of the borders. Since the vast majority of the patterns are elongates or equiforms it is legitimate to refer to centres and borders. When the same species were present on both centres and borders the individual plants would be stunted and commonly adpressed on the centres and more vigorous on the margins. The most common types of vegetation assemblage are listed below.

Table 1V. Vegetation Assemblages found on the Pattern Centres

C1 Bare ground (zero vegetation as in Plate 1) with or without any of the vegetation assemblages mentioned below. A combination of bare ground and vegetation could either be with definite alternating patches (Plate 6) or an approximately even open vegetation with bare spaces between (Pate 41).

C2 Lichen dominated assemblages, with or without low heaths and herbs (Plate 30).

C3 Assemblages dominated by low heaths and herbs, with or without notable amounts of lichens (Plate 19).

C4 Various assemblages with dominant or very conspicuous grass, with or without low heaths, herbs and lichen. Sometimes with scattered willow and grass tussocks (Plate 8).

C5 Assemblages dominated by tussock grass, usually with scattered birch, willow and heaths (Plate 33).

Table V. Vegetation Assemblages found on the Pattern Margins

M1 Assemblages with dominant dwarf birch, with or without willows, heaths (especially Vaccinium uliginosum 'blue berry'), (Plate 26).

M2 Assemblages with dominant willow, with or without birch and heaths (Plate 8).

M3 Assemblages dominated by grasses, with or without willow, birch, herbs and heaths (Plate 41).

M4 Assemblages dominated by tussock grass with notably large numbers of willow, birch and heaths (Plate 33).

Any of the species dominating one part of a pattern may be present on the other part of the pattern. Thus few patterns are without any dwarf birch on the central area, though it is usually extremely stunted and adpressed. True mosses were not often prominent members of the various assemblages, though subsidiary quantities were commonly present in the marginal areas. It is worth emphasising that there were many gradations between vegetation assemblages mentioned above.

The commonest combination of vegetation was dwarf birch margins with bare soil or lichen covered centres (M1 and C1 or C2 as in Plate 26). Another very common combination not shown well in any of the plates was willow dominated margins with grass centres (M2 and C4), often looking degenerate or inactive. Table V1 below summarises other combinations observed.

Table V1. Vegetation Combinations Observed

Vegetation of Centres	Vegetation of Margins	
C2 or C3, often with C1	M1	Most common
C2, C3	M3	Occasional
C4	M2 or M3	Common
C4	M1	Occasional
C5	M4	Occasional
C5	M1-M4	Fairly common
C4-C5	M2	Fairly common

(Where two categories are joined by a hyphen an intermediate form of vegetation was notable.)

In addition to the intermediate vegetation assemblages shown in the table many other intermediate assemblages were seen. Certain combinations of vegetation were definitely not observed.

Table V11. Vegetation combinations definitely not observed

C1	M2, M4
C2	M2, M4
C3	M4
C4	M4

4.2.3 Variations of Relief of the Patterns

Figure 19 shows a series of idealised cross profiles ranging from raised centres to raised margins to both raised centre and margin. More complex relief than this was sometimes seen as combinations of the forms shown in figure 19, or due to smaller patterns being superimposed on larger ones, and occasionally other variations were seen. The relief of a pattern was frequently visually modified by the vegetation growing on it (see plate 19). The relief of many patterns seems to vary in amplitude through the seasons - being at a maximum in late winter and a minimum at the end of the thaw season. The actual relief form does not seem to vary, though it is possible that some 'gently rolling' relief forms at the end of winter might become 'sharply raised central area' forms at the end of the thaw season. The majority of the latter category, however, seem to have the same form throughout the year, though they vary in amplitude. The 'gently rolling' relief of site D5 (Plate 21) subsided to a very low amplitude during section excavation, almost certainly due to thaw of the ice in the pattern.

The relief of smaller forms of patterns was generally simple, and they were frequently flat. The hummocks seen in Plate 49 were the only example of this type seen in the Seward Peninsula. All ice wedges observed with relief were depressed margin forms. The margins of many 'sharply raised central areas' were frequently in the form of a roll of turf (see plate 6 and figure 15). On some pattern sites, and particularly site C2, there were ridge features at intervals amongst features that would otherwise be described as stripes (see Plate 11). These ridge features were so prominent as to perhaps be described as steps. Every gradation between these ridges and elongates with a slightly raised downslope margin was observed. Whilst there were few isolate step features observed in the Seward Peninsula it was clear that steps can grade to elongates.

4.2.4 Combinations of Relief and Vegetation

Certain variations of vegetation were more commonly associated with certain types of relief of the patterns as shown below.

Table VIII

Relief Type	Vegetation on Centre	Vegetation on Margin	Recorded Variants
(a) Flat	C1, C2, C3, C4, C5	M1, M2, M3, M4	12
(b) Raised centre	C1, C2, C3, C4	M1, M2, M3	10
(c) Sharply raised centre	C1, C2, C3	M1 (M3)	5
(d) Raised margin	C1, C2, C3, C4, C5	M1 (M2, M4)	5
(e) Raised centre and margin	C1, C2, C3, C4, C5	M1 (M2, M4)	6
		TOTAL	38

Thus considering vegetation and relief alone some thirty-eight variants were recorded, as well as intermediate observations. It would be possible to regard each of these as a unique type of patterning. When the intermediate forms are considered, and the general similarities between all the 'types' then the idea of considering all these ase uniquely different is ridiculous. It might be suggested that these variants represent a number of different pattern types and intermediate forms. The overall variation observed did not suggest that these patterns might be intermediate forms between different end members. Some of the variations are undoubtedly due to differing activity of the patterns, though again with no suggestion of fundamental differences of the pattern forming and maintaining processes. The present writer concludes from these surface observations that there is considerable variation of both vegetation and relief marking of a single type of patterning. In this 'single type of patterning' a number of processes and factors may well be acting in differing proportions, but the same fundamental controls seem to be present in all these patterns.

4.2.5 Variations of Stone marking the Patterns

One one site a complete variation from patterns with vegetation margins to patterns with stone margins was seen in the same integrated network (site X4, see Plates 35 and 36). Within this area some of those patterns that were marked by vegetation margins had concentrations of stone beneath the margins. The presence or absence of stone borders seemed to depend upon whether or not there was stone available. On another site there were suggestions of stone concentrations associated with thick peat under ridges. Stone patterns were also observed isolated from other patterns (see Plate 43).

These observations seem to demonstrate that in the large patterns of the Seward Peninsula stone borders are simply another variant of the fundamental pattern type. This inference may be of great importance in deducing the type of processes that are involved in forming patterns.

4.2.6. Variations of Pattern Size

The elongate 'large' patterns of the Seward Peninsula were usually about 6 m average width or a little more, ranging from 5.5 to 7.0 m from site to site. Occasional patterns were as small as 4.5 m or as large as 8 m wide. The equiforms were about 8 to 9.5 m diameter, though occasionally outside this range. Many exact measurements were lost when field notes (and other articles) were stolen. A typical series of 7 equiforms were mean diameter 8.25 m, standard deviation 0.7 m; range 6.3 to 10.3 m. Attention is drawn to the special note on Hopkins and Sigafoos measurements in section 4.3. Very similar patterns observed in Central and Eastern Alaska (see Plates 65 and 67) were perhaps a little smaller. A few small samples measured gave equiform diameters of 6 to 8 m and stripe widths of 4 to 6 m.

The ice wedge polygons observed in the Seward Peninsula were all notably larger than this, though air photos suggest that smaller ones were present on the Kuzitrin Flats (inaccessible in summer). The 'medium sized' patterns had equiform diameters of about 1.5 to 2.5 m (see Plate 47). No medium sized elongates or stripes were seen in the Seward Peninsula, but excellently marked medium sized vegetation stripes about 1.5 m wide were seen in Central Alaska (Plate 66). Miniature patterns about 15 to 20 cms diameter were seen on bare soil areas (Plates 2, 3, 4, 39, 40).

Thus there were patterns of four different sizes. These patterns were distinct and there was no sign at all of a continuous series of pattern sizes. As mentioned above two or more different sizes could occur superimposed. It is likely that occasional ice wedge polygons would be as small as occasional 'large' patterns. Similarly a few small 'large' patterns might be as small as occasional large 'medium' patterns. On no site, however, was there any suggestion of a trend for one size of patterns to pass laterally into another general size.

4.2.7. Variations of Pattern Form in Section

Only a small number of full sections were recorded, and a few others inferred from limited excavation and augering. Since there was considerable variation in a limited sample it is necessary to describe each section on a site basis before attempting to generalise.

At site F2 there was a large section across many elongates. The patterns were marked by raised centres dominated by lichens ('reindeer moss') with occasional patches of bare ground and depressed margins dominated by birch (see Plates 26 and 27). A striking feature of this section was the variability of the structure of each individual pattern. In this section bedrock at depth passed upwards to disorientated rock fragments with silt infilling the voids at about 1 m from the surface. There was a fairly continuous layer of surface peat that was notably deeper under all the margins of the patterns, though the actual thickness of 'deeper' peat varied from 15 to 40 cm. Other features varied considerably from pattern to pattern. No structure was detected in some patterns although they were very carefully examined (see left hand side of Plate 26). Other patterns showed lobes of peat extending in arcuate form towards the centres of the patterns (right hand side of Plate 26 and figure 8). There was virtually stone free silt above the arcuate lobes, contrasting strongly with the very stony material below. Whilst some of the variation along the section was because it was only approximately at right angles across a series of stripes, much of the variation was due to variation of structure from pattern to pattern.

In a nearby pattern area a section was excavated across an elongate with similar relief but much less vegetation (site D.5, see Plates 21-23 and figure 7). This section showed similar structures to some seen in the previous section. The basal material was stones with silt filling the interstices. This material penetrated to the surface of the raised area. Under the marginal depressed area there was deep peat with arcuate lobes of peat extending towards the centres but curving up towards the surface before they reached the middle of the raised areas. Above the peat lobes were areas of stone free, strongly mottled silt. The relative distribution of materials in this section suggested that the peat lobes were not simply buried surface layers.

A section was excavated across an equiform at site X4 (similar to the equiform shown in Plate 29). Thick peat was found under the raised margin of this pattern, though there was a large difference in amount of peat from one side of the pit to the other (compare figures 11a and 11b). Shallow sections cut nearby suggested that the amount of peat shown in figure 11a was the minimum for any pattern at this site. Under or amongst the thick peat there was a minor concentration of stones. There was no other obvious structure in the section. A slight difference of stoniness was noted, with fewer stones in the areas flanking the thick peat. Some patterns in the same integrated network had relatively thin peat overlying stone concentrations and other patterns had margins that were marked by stones and not vegetation.

A further site was excavated in a pattern with no obvious relief but very well marked by contrasting willow and a grass-herb association (site C2, see Plates 7-10 and figure 5). The section was almost entirely silt and peat with only rare stones. Peat was very prominent under the 'margins' (the willow area). Peat extended continuously or only slightly interrupted under the central areas. A longitudinal section also showed the notable continuity of this peat. The absence of roots or any sign of oxidation of the silt below this peat layer indicated that this was not buried surface peat. There were less regular intercalations of peat and mineral soil on the flanks of the deep peat under the margins, but it was not possible to determine which material had been injected into the other. During the course of excavation of the pit all the frozen silt showed abundant Taber ice lenses ('ice gneiss' appearance). The frozen peat showed only irregular interstitial ice.

Hopkins and Sigafoos (1951) excavated a section through a pattern essentially similar to those being described here, as shown in figure 17. In the present study a limited excavation near Salmon Lake appeared to be very similar though the excavation was not large enough to allow detection of definite uplift of material under the pattern centre.

At site E2 patterns were found which seemed to have no differentiation whatsoever of the materials in section, not even a deeper peat under the 'margin' areas.

Whenever the depth to frozen ground was measured it was much less under the margins of patterns than under the centres. (N.B. No measurements from stone marked patterns.) On some sites, especially C2 and D5, there was a grey brown silt above a dark grey silt with a greenish tinge. This change of silt colour, which also coincided with the maximum penetration of roots, seemed to mark the permafrost table. On sites with suitable materials areas of voids between stones were found at about the estimated depth of the permafrost table, though only at site F2 were these voidal areas continuous across the patterns. Average depth of thaw of the materials in the patterns seems to be between 40 and 70 cms for the peat (margin areas) and about 1 m or a little more in mineral soil under pattern centres. All the sections of large patterns are brought together for comparison in figure 20.

The sections through ridge features across the stripe forms at the western end of Labaree Hill are shown in Plates 11-16 and figure 6 and require no further explanation here. It is worth emphasising that there were ridges in the frozen ground coinciding with the surface ridges.

4.2.8. Variations of Materials in the Sections

Reference to figures 83 and 85 shows that all the pattern sites had silt rich mineral soil present. Hopkins (1963) describes widespread thick windblown silt in parts of the Seward Peninsula and the silt in most of the sections was probably wind blown. Two examples of undoubted loess are given in figure 83 for comparison. There were notable amounts of clay present ranging from 2.3 to 7.9% - higher than might be expected for arctic conditions (Hill and Tedrow 1961). Stones present on the pattern sites varied from angular local bedrock (dominantly schist) to sub-rounded or rounded glacial and fluvio-glacial material.

As in the case of the patterns reported by Hopkins and Sigafoos (1951) patterns were not found in areas of deep peat. The peats associated with the patterns were all eutrophic, and some had a pH as high as 8.5. Tedrow, Drew, Hill and Douglas (1958) comment upon the extensive areas of arctic Alaska that have unexpectedly high calcareous content. Some of the patterned sites also showed very carbonate rich groundwater.

Patterning was not found in areas where the soils were deficient in fines. It was notable that the large patterns near the Denali Highway, Central Alaska, were developed on areas reported by Pewe (1965) as generally silt rich till and were not developed on tills and fluvioglacial deposits without notable amounts of fines.

A section through relief equiforms (hummocks) on the Salmon Lake end moraines is shown in plate 49. The sections indicated that the material in the hummocks had been ejected from below. The analyses indicate that the finer particles have been selectively ejected (see figure 83d).

4.2.9. The Transition from Patterned to Non- Patterned Areas

Patterns are abundant in some areas and absent in others. In many cases one site may have well marked patterns and another have no trace of patterns, although they both appear to be identical sites. Patterns were observed to fade where there was a change of material from fine to coarse deposits, where bedrock came near to the surface, where the supply of stones faded (stone patterns), where there was a marked change of slope and therefore presumably drainage conditions (or possibly other factors) and also patterns sometimes faded where there was a change of vegetation, though presumably this would be linked to some other factor.

4.2.10 Air Photograph Interpretation

Where air photographs of suitable scale and quality were available the patterns were readily distinguished. Much of the cover that was used was small scale so that only the best marked patterns could be recognised (see Plates 17, 18, 24 and 28). Figure 21 gives examples of the air photograph mapping. The classes used in the mapping were equiforms, meandroids, meandroids with definite elongation, elongates, clear stripes, ice wedge polygons, solifluction lobes, and 'vague patterning'. The class 'meandroids' is one used solely for definite patterns that cannot be classified into stripes, elongates, equiforms or steps. This may be because of the photo quality or it may be because of the pattern marking on the ground (see especially Plate 81). Meandroids without elongation could be any form of large patterned ground including ice wedge polygons. Clearly meandroids with elongation cannot be ice wedge polygons. Ground observations suggest that most of the patterning mapped as 'vague' was poorly marked ice wedge polygons (or fossil ice wedge polygons). Other periglacial features such as solifluction lobes and pingos were readily recognisable. The air photograph studies in Alaska are described in detail in Appendix F.

4.2.11 Distribution of the Patterns

On the ground the patterns were best marked in the Central Seward Peninsula, and declined in their clarity of marking southwards, though good examples were still found near to Cape Nome. This observation was confirmed on the air photographs. An air photo traverse tended to reflect the scale and quality of the particular print being used, rather than the true pattern abundance. Figure 21 shows two areas with widespread pattern cover, though many areas had much less patterning.
The percentage of the area covered by patterning seemed to be crudely comparable to the percentage of cover by patterns in East Anglia, U.K.

On the ground nothing like as high a percentage of the ground was seen to be pattern covered. This is again similar to observations in East Anglia.

An interesting feature of the local distribution of the large patterns was that they were best developed where drainage conditions were a little more favourable than usual. Patterns are not found in the centres of extensive flat areas or the lowest slopes adjacent to poorly drained river valleys.

Hopkins (personal communication) reports that the patterns are present throughout the Seward Peninsula. The 1951 paper by Hopkins and Sigafoos describes the widespread vegetation patterns around Imuruk Lake, Seward Peninsula. The patterning there seems to have been less variable, particularly in the vegetation marking, than the patterns recorded in this thesis, possibly because the thick silt deposits of the Imuruk Lake area provide more uniform conditions. Similar patterns were seen in the glaciated areas of Central Alaska on tills and loess south of the Alaska Range (see Plate 65). Extensive areas of patterns were seen above the tree line in the unglaciated area between Tetlin (Eastern Alaska) and Dawson City (Yukon). It is likely that the large patterns continue through suitable areas of Northern Canada. The omission of any mention of similar patterns by such observers as Brown J. (1965, 1966) suggests that North of the Brooks Range this type of patterning may be absent or rare.

4.3 PATTERNS OF THE SEWARD PENINSULA DESCRIBED BY HOPKINS AND SIGAFOOS

The paper by Hopkins and Sigafoos (1951) entitled "Frost Action and Vegetation Patterns on Seward Peninsula, Alaska" is a long and detailed description and interpretation of patterns largly from the Imuruk Lake Area. This section will only attempt to summarise the most important parts that either support or contradict the observations and conclusions of the present study. The botanical descriptions and interpretations are much more detailed than any attempted in this thesis. The vegetation patterns described by Hopkins and Sigafoos are interpreted as the products of the interaction of vegetation and congeliturbation, Frost Scar is a term selected for areas of bare soil scattered amongst vegetation. This term has been adopted in the present study. Frost scars are initiated by animal activity or by locally greater frost heave. Once a frost scar is established the thaw beneath the bare ground will be deeper than under adjacent vegetation and hence a basin develops in the permafrost table. The dilation of the ground above such a basin will be greater so that the scars tend to be convex in spring and concave in autumn. Miniature zellenboden are commonly present on the frost scars and are interpreted as dilation cracks. The activity of the zellenboden with seasonal dilation and the action of needle ice around the scar margins perpetuate the frost scars by preventing recolonisation.

Cottongrass tussocks are described in detail and an explanation for the mounds of mineral soil beneath the tussocks is advanced. During freezing the tussock insulates the ground below so that bare soil nearby develops a frozen layer before the soil under the tussocks. Heaving pressures developed at this stage will be most easily relieved by raising the unfrozen soil under the tussocks. Repeated cycles over many seasons raise a mound under the tussocks.

Peat Rings are frost scars surrounded by a ridge of peat produced by frost action. As in the case of frost scars there is a basin in the permafrost table under the bare soil area. There is evidence of movement of peat from the ridges along the base of the active layer to the centres of the pattern. The peat rings were noted to be elongated on slopes and commonly arranged in trains extending downslope. Despite the fact that the size of peat rings is said to be 4 to 12 feet diameter the air photograph published shows grouped or integrated peat rings much more uniform in size than these figures suggest (see also note on size below).

Tussock Rings and Tussock Groups are stages of the colonisation of peat ring central areas by cotton grass tussocks.

Tussock-birch-heath polygons are fully integrated networks, the polygons being described as becoming elongated on slopes. A cross section is reproduced here as figure 17. There is evidence of movement of peat from the peat margins along the base of the active layer towards the centre of the pattern, and also evidence of peat moving upwards in the pattern centre. The tussock-birch-heath polygons are described as appearing to be relatively old and stable features, though still active. They are thought to have been present in the area since climatic conditions have been suitable.

When explaining the pattern development considerable emphasis is laid on the consistent presence of silt rich mineral soil and moderate amounts of peat giving rise to differential heave. The mineral soil has a capillarity favouring migration of moisture to ice lenses. It also has a greater thermal conductivity so that the depth of thaw is greater which allows greater heaving. Peat heaves less due to poor capillarity and thermal conductivity and also "because the tough fibrous structure of the peat resists disruption by growing ice crystals" (Hopkins and Sigafoos 1951 p 61).

Horizontal movements across the surface of the pattern are not clear. In the case of the tussock-birch-heath polygons peat is reported as being 'shoved' from the centres to the margins. In other cases miniature zellenboden were found conforming to old vehicle tracks suggesting that at least over a period of a few years horizontal movements did not take place. In general, however, the distribution of peat in the sections suggested to Hopkins and Sigafoos a movement similar in form to that of convection currents.

Hopkins and Sigafoos noted that tussock-birch-heath polygons are found on better drained sites and also that peat rings are commonest on slopes with a southerly aspect. Patterns of similar types are thought to be widespread throughout the Arctic and are likely to be found fossil also, though it is noted that "Similar features in other parts of Alaska differ considerably in certain details".

Creep and viscous flow are noted in connection with the patterns, though viscous flow is thought to be at a minimum in tussock-birch-heath polygons because water is only abundant in the spring when the ground is only unfrozen for a few inches. Snow is thought to be important in modifying the freezing processes, especially if it falls before the final freezeup. Snow tends to drift on to bare soil areas because they are depressed compared to the surrounding vegetation.

The detailed mechanism of formation of the tussock-birch-heath polygons proposed is that they originate as random frost scars and develop to an integrated pattern.* The frost scars are thought to go through a series of stages similar to the peat rings, tussock rings and tussock groups. More scars develop until a network of closely spaced tussock areas is produced. Drainage is then concentrated in the marginal channels. Peat pushed from the centres fills many of the channels. In a winter season the early frosts produce a surface layer of frozen ground in the soil of the centres (see figure 18). The peat of the channels is rigidly frozen at the surface and anchored downwards by roots and stems. As freezing continues and pressures continue to develop the mineral soil of the centres thrusts laterally into the peat. This lateral thrust displaces some peat which is forced downwatds into the still unfrozen zone beneath the centre. The peat areas between two centres is not heaved upwards because the frozen surface layer plus plant roots and stems in strong enough to resist heave. The peat movement upwards in the middle of the pattern centre is thought to occur at a later stage when the peat has been distributed right across the base. The upward movement is part of the upward movement into the bases of the tussocks.

The present writer agrees with the majority of observations and ideas put forward by Hopkins and Sigafoos but differs on the questions of pattern sizes reported and certain important aspects of the mechanism of formation.

Footnote* Hopkins (personal communication) stated that he probably underestimated the importance of caribou and reindeer in initiating frost scars. Since publishing the 1951 paper he has seen that these large mammals "wreak havoc wherever they graze".

It is notable that the pattern sizes given by Hopkins and Sigafoos do not agree with the sizes given in the present thesis. Hopkins pointed out to the present writer in the field essentially identical patterns near the Kuzitrin River. The size of these patterns conforms to those reported in this thesis. However, for the patterns around Imuruk Lake, Seward Peninsula, Hopkins and Sigafoos report the tussock-birch-heath polygons as varying from 7 to 15 feet diameter (2.1.to 4.6m). Despite this size range quoted their main pattern section shows a pattern some 20 feet (6.1 m) across. It seems possible that Hopkins and Sigafoos quoted sizes of the central areas and not the overall diameters or widths. Figures for the size of central areas at site X4 correspond closely to the Hopkins and Sigafoos figures. This almost certainly applies also to the sizes quoted for peat rings.

4.4 SUMMARY AND PRELIMINARY INTERPRETATION

A wide variety of surface markings by vegetation, relief and stones were recorded on patterns with equiform diameters of about 8 to 9 m and elongate and stripe widths about 6 to 7 m. From surface markings and particularly from the uniform size and numerous gradings from one pattern marking to another, it seems that all these 'large' patterns are produced by a similar process or set of processes.

A smaller sized pattern, about 1.5 to 2.5 m diameter, was often seen superimposed on the large patterns. A small number of areas of patterns of approximately this size were also seen not associated with the larger patterns. On one site large elongates were noted to be clearly aligned some 10 degrees different from the line of maximum slope.

The pattern forming processes were thought to be active in the area of the Seward Peninsula for a number of reasons. Very active, probably freshly developed, grouped frost scars of the large size were seen on one site. Another site showed regular contiguous patterns clearly in the vegetation but with no subsurface differentiation. These would quickly disappear if the pattern forming processes were inactive. On a number of sites the subsurface differentiation was small, so that again these would quickly disappear if the pattern forming processes were inactive.

Notwithstanding this evidence of activity of the processes in the area some of the strongly differentiated patterns may be only partially active. The problem of deciding whether or not an individual site is active or just 'ticking over' is a difficult one. Once a large pattern has developed well differentiated subsurface features it is likely that frost action would maintain some activity even after the permafrost had gone. The presence of silt at a shallow depth would allow some small frost scars under conditions very different from pattern forming conditions. The assessment of activity of patterns could perhaps be divided into two:-

(a) Processes of pattern initiation still active

(b) Patterns still show some signs of activity but pattern initiating processes not active.

Using these criteria the general conditions in the Seward Peninsula field area seem to include 'initiation conditions,' though probably not on as wide a scale as in the past. Near the south coast pattern initiation is possibly only active on specially 'favoured' sites.

The pattern sections show considerable variation of form varying from no differentiation to a well organised distribution of different materials. Figure 20 summarises the pattern sections studied. The other sizes of patterns in the area seem to be quite distinct, whereas all the large surface patterns are of the same general type. Similar pattern sections were seen with different surface markings and similar surface markings had a variety of structure in section, even in one section. There may be a large number of different processes forming by coincidence similar surface forms. Alternatively there may be one process or group of processes developing essentially similar patterns but with variable structures due to variations of materials, amount and form of vegetation, the length of period the patterns have been developing and other factors. The assembled evidence is strongly against the first hypothesis and definitely in favour of the second, i.e. all of the sections shown in figure 20 are produced by the same process or group of processes acting in a similar way but producing variable structures because of local variations. When other geomorphological processes are considered many other examples of varying details of section produced by the same process spring to mind. Ice wedge polygons have a variety of surface forms and sections within certain limits, yet undoubtedly they are formed by the same basic processes (Drew and Tedrow 1962, Svensson 1963, Pewe 1965).

Most of the patterns have deeper peat beneath the margins. Some have peat extending from these deeper peat areas under the centres of the patterns, at least in part following the base of the active layer. Sometimes after following the base of the active layer for a distance the peat curves upward toward the surface. In other sections the peat follows the base of the active layer right across beneath the pattern centre. Some poor evidence was seen for injection of silt from the centres into the deep peat of the margins. Hopkins and Sigafoos (1951) report good evidence of such an injection. Above the peat in arcuate form from the margins to the centre there is usually an area of stone poor silt. Other sites show similar areas of stone poor silt without any peat lobes. Studies of arctic soils have shown widespread buried peat (Douglas and Tedrow 1961, Tedrow and Brown 1965, Brown J. 1966).

This has been interpreted as resulting from climatic change (Douglas 1961). J.Brown (1966) after working on the soils of the Okpilak River region, North East Alaska, "believes that the occurrence of these buried (peat) surfaces and present frost scars are related. That is, the buried organic matter is also the result of comparatively recent frost scar development" (p 11).

The thicker peat under the margins may have developed due to greater plant growth in the margins, due to better preserving conditions or due to peat from the centres being pushed to the margins. All three factors probably contribute, though the relative importance of each cannot be estimated from the present study.

The actual movement of peat from below the margins along the base of the active layer and also upwards in the pattern centres is clearly demonstrated by both the sections produced in the present study and by the sections by Hopkins and Sigafoos (1951).

The relatively stone free areas of silt flanking the margins, with or without peat lobes below, are problematic. These might be material from which stones had been removed by sorting. This may represent fines ejected from more stony material below (as in the case of the earth hummocks seen in Plate 49). The appearance in some cases seems to suggest that this material has been pushed to the sides by upheaval of material from below, which may also suggest the stone poor material is silt, blown in at a later date. If any of the above hypotheses are correct it is surprising that the analysis of samples reveals little difference between the stone poor silt and the matrix of the stonier material below. Possibly the absence of any peat fragments is significant. The present writer is unable to explain these features, but emphasises that they do not seem to be a casual feature of the patterns. Any full interpretation of the mechanism of development of the patterns of the Seward Peninsula will need to explain this feature, which does not seem to have been previously reported on patterned ground sites.

Other periglacial features of the Seward Peninsula are described in Appendix A.

5.0 STUDIES IN THE BRITISH ISLES

5.1 GENERAL INTRODUCTION

The studies in the British Isles were mainly in East Anglia. Most of the British Isles were covered by ice at some time during the Pleistocene. Figure 23 which is taken from West (1963) summarises the knowledge of the British Pleistocene ice advances.

Clear evidence of three glaciations has been found in Britain. In decreasing order of age these are the Lowestoft Glaciation, the Gipping Glaciation and the Weichsel Glaciation. A series of retreat stages of the Weichsel (most recent) glaciation can be detected, though there is still considerable disagreement as to the extent, numbers and ages of the retreat stages. The main summary works with details of the glacials of the British Isles are Wright (1937), Zeuner (1945 revised 1959), Charlesworth (1957), West (1968). Probably the most striking change in recent years has been the rejection of the Alpine Type Site names for correlations in North West Europe (Gunz, Mindel, Riss, Wurm) and the adoption of type site names from North West Europe (Elster, Salle, Weichsel, etc).

5.2 CHRONOLOGY AND DEPOSITS OF THE PLEISTOCENE OF EAST ANGLIA

Periglacial studies in Britain have been neglected until recent years, but are now developing (Fitzpatrick 1956, 1958, Shotton 1962, Waters 1965).

The general area of East Anglia has proved very important in dating and correlating the various stages of the Pleistocene. Many of the names of stages of the British glacial sequence are taken from East Anglian type sites - Cromer, Lowestoft, Hoxne,Gipping, Ipswich (not to mention the earlier Pleistocene). Table IX shows the East Anglian sequence as referred to in this thesis.

A whole series of names have been and to some extent still are used for the most recent glacial in England - Newer Drift, Hessle (Yorkshire type site), Hunstanton (East Anglia), Wurm (Alpine) and Weichsel (Germany). The present writer subscribes to the view that local type site names should be used until wider correlations have been very definitely established (see West 1963, especially discussion). In the case being discussed here (the most recent glaciation), it seems that the correlation with other North West European sequences is proved beyond reasonable doubt and the name Weichsel may be applied in the British Isles, and in particular in East Anglia where much of the evidence originates. The older name, Wurm, from the Alpine sequence, seems inappropriate in view of the low level of correlation between Alpine and North West European sequences*.

Footnote* The author apologises to many readers for setting out in some detail this point which is now widely accepted by most Pleistocene workers. It was, however, deemed necessary in view of the continuing habit of many Geographers and others to retain the term 'Wurm'.

Table IX (after West 1963 and others - See Appendix B.5)

Pleistocene Sequence in East Anglia

Stage	Climate	Deposits
Flandrian	Warm	Varied
Weichselian	Cold	Hunstanton till (only in extreme north of East Anglia).
Ipswich	Warm	Interglacial deposits at Bobbitshole.
Gipping	Cold	Till in localities throughout almost all East Anglia.
Hoxnian	Warm	Interglacial deposits at Hoxne.
Lowestoft	Cold	Till at scattered localities over most of East Anglia. Corton Sands } Cliff sections of north and North Sea Drift } east sea coasts.
Cromer	Warm	Upper part of Cromer Forest bed.
Various		Evidences of warm and cold periods in Crag deposits.

5.3 PREVIOUS ACCOUNTS OF THE PATTERNED GROUND OF EAST ANGLIA

Surprisingly the widespread form of patterned ground in East Anglia has been undetected, or at least uninterpreted, until relatively recently. The patterned ground was first described briefly by Watt (1955) as stone stripes in Breckland. Shotton (1962) mentioned the patterned ground in East Anglia in a more general paper. Perrin (1963) described the use of air photographs in interpreting the patterned ground of Breckland. Williams (1964) wrote a general account of the patterns and mapped the patterns from air photographs, not only in East Anglia but also in adjoining areas (particularly, limited areas of Lincolnshire and the North Downs). The present study began in 1963. Watt, Perrin and West published a paper entitled "Patterned Ground in Breckland: Structure and Composition" in 1966. This paper contained considerable detail on the drifts of Breckland, but was related to very few specific pattern sites. Further details of the observations and ideas put forward by the above authors are reported in the following sections.

5.4 GRIMES GRAVES PATTERNED GROUND SITE

This site will be described in some detail in the main text and other sites only described where they demonstrate new features or reinforce important generalisations. More detail on numerous points in the main text can be found in Appendix B.

Figure 24 shows the general location of the site, which is an area of very well marked patterning surrounded by afforestation. The well known Neolithic flint axe factory site, Grimes Graves, lies some 600 m to the east south east of the main excavation.

Surface Form of the patterns.

The very obvious stripe form of the patterns can be seen on the air photographs of the site (see Plate 68). The patterns are marked by alternate strips of heather and short grass. The slope is 2° and the stripe widths average 6.9 m, but are very variable (see Table D2 Appendix D). Preliminary augering demonstrated that the soil under the short grass was sandy for 10 to 20 cm, with chalk rich material below. Under the heather areas the soil was sandy with no chalk for at least 50 cm. There was a difference of up to 3 pH units between the pH of the surface soil under the grass (average pH 7) and under the heather (average pH 5).

Form of the Patterns in Section

Plate 69 shows the main excavation in relation to the stripes. Plate 70 gives a general view of the section. Figures 25 and 26 are detailed drawings of the section.

The section was at first sight very complex. The most obvious features were the generally white (chalk rich) appearance and the 'troughs' of sand corresponding to the heather stripes on the surface. Further examination of the section shows that there are a series of materials present viz:

1. In situ chalk at the base of the section.
2. Disordered coarse chalk fragments ('chalk rubble').
3. Various grades of intimately mixed sand and chalk.
4. Sand which is chalk free.

In different parts of the section there were varying quantities of stones, mainly flint. Some flints were unweathered except for simple fracturing. Others were frost spalled, wind polished and some fretted as if by solution. A man worked flint was found which is discussed in detail in Appendix K. A very few well rounded sandstone pebbles were found (probably derived Bunter).

The materials were not distributed in the subhorizontal layers normally expected in soils. The section is easiest described in terms of three inter-related areas - the basal area, the 'buried ridge form ' and the 'buried trough form'.

At the base in situ chalk passes up with no definite break to chalk rubble. In places the top beds of chalk appeared to have been upheaved (see Plate 72 and figure 27).

In the ridge form a variety of materials ranging from chalk rubble to sand rich sand chalk mixture were found. The sand chalk mixture was notably sandiest near the base, rather than nearer the surface as might be expected. In figure 25 upward extending features of various shapes are prominent. These have a wide variety of forms and the term 'pseudopod' has been selected to avoid the limitations of the terms tongue, lobe, involution and so on (See Appendix B.122). Figure 28 shows a variety of forms considered to be covered by the term pseudopod. In the centre of each ridge form at this site there was a particularly large pseudopod which can be described as a 'central dyke form', since it was continuous up and down slope (see Plates 73 and 74 and figures 25 and 26). The other pseudopods were not so continuous in three dimensions. At right angles to the contour they varied in width from a few cm to a metre or so, so that a plan section through a pseudopod was generally a flattened oval shape. The pseudopods were inclined downslope at somewhat varying angles when viewed in section at right angles to the slope (see Plate 75).

The stones in the ridge area can be considered in two groups. Firstly the large flints unweathered except for simple fracturing were found closely associated with the distribution of chalk rubble. The large flints were especially concentrated in the dyke forms (see Plates 73 and 74) though they were also found in other pseudopods and in the upper part of the chalk rubble zone below (though not in the lower part). The second group of stones in the ridge area were the weathered flints and allochthonous stones. These were distributed in association with the sand chalk mixture, particularly the sandier areas, though these stones were only a small percentage of the material.

The infilled trough forms were relatively simple (see Plate 76) though the troughs were commonly modified by small pipe like downward extensions. The main material in the troughs was incoherent sand. Flints were unevenly distributed through the sand in no discernible overall pattern. Some areas of sand were relatively clay rich, especially in the small pipes and adjacent to the sand chalk mix. These clay rich areas are often referred to as 'clay shift' by local pedologists but generally contain only 5 to 10% clay.

In the chalk rubble zone across the base there were open voids between the chalk rubble particles, sometimes perhaps as much as 50% of the volume. This contrasted strongly with the nature of the buried ridge area above which was notably compacted and very much more difficult to excavate than the in situ chalk. The sand chalk mixture of the ridge form was markedly laminated. The laminae were 2-10 mm apart and are marked by the sand having no chalk matrix and probably also the amount of sand being diminished. The laminations were generally sub parallel to the surface, but turned upwards at the junction with the pseudopods. Rare examples were found of laminations extending across smaller pseudopods. (see figure 29).

<u>Preliminary Interpretation</u>

The surface features require little preliminary interpretation. The patterns in this area are particularly well marked vegetation patterns.

The vegetation differentiation is related to differing soils. This is particularly well marked because on this site the soil has not been generally disturbed for some time and hence there has been plenty of time for the vegetation to establish itself in equilibrium with the conditions.

The chalk rubble at the base is clearly derived from the underlying in situ chalk and equally clearly the chalk rubble in the pseudopods comes from the same source. The mechanisms for developing the pattern features and the origin of the sand and sand chalk mixture will be discussed later.

The very large flints, unweathered except for simple fracturing, appear to be related to the chalk rubble. The latter is derived from the underlying solid chalk. The suggestion is that the large flints are also derived from the underlying chalk. It was noted above that there were no large flints in the in situ chalk. The present writer suggests that at some time in the past the large flints formed a semi-continuous layer which has now been largely 'concentrated' in the centre of the ridges. Layers of flint of the type envisaged can be seen in the nearby Neolithic flint mines. This hypothesis was tested by further excavation near the main section. The chalk is almost horizontal at this site and thus it was predicted that this postulated layer of flints should still be present farther upslope. Excavation proved just such a layer at 1.85 to 1.95 m depth, corresponding to a depth of about 1.6 m in the main excavation. Despite excavation to 4 m no further large flints were found. Thus there is clear evidence that the concentration of flints in the central dykeform was derived from an original horizontal layer at around 1.6 m. This is important in indicating the way that material moved when the pattern was active.

5.5 KNETTISHALL PATTERNED GROUND SITE

The patterns of the area around the site (Grid reference TL 964 804) can be seen in figure 46.

Surface Form of the Patterns (see Plates 77, 78 and 79)

The patterns were stripes, though at the lower limit of stripes according to the present writer (see section 2.44). The contrast of the pattern markings varied from excellent to poor during the period of study. The average pattern width is 6.8 m and the slope is 2 degrees.

Form of the Patterns in Section. The Knettishall section (see figures 30, 31, 32) showed broadly similar structures to those seen at Grimes Graves, with some small differences and some additional features. The in situ chalk was much less well bedded. There was a very much higher percentage of allochthonous stones and the weathered flints included some that were clearly water rounded. As at Grimes Graves fresh flints were distributed in relation to the percentage of chalk, and weathered flints and allochthonous stones were distributed in close relationship to sandiness of material. The depth to in situ chalk was notably greater than at Grimes Graves (2.5 to 2.6 m).

In the buried ridge form the pseudopods were much less well marked at this site, though clearly present. There was no 'central dyke form', though the central pseudopod was larger than the others and more persistent in three dimensions. All pseudopods in three dimensions showed a distinct inclination downslope, commonly at an angle of 60 degrees to the vertical (see especially figure 31a). Additional features were the tongues of sand penetrating along the base of the ridge from the sand trough areas (see figures 30 and 31b).

The infilled trough forms and the sand over the ridges were both deeper than at Grimes Graves. There were well developed pipes projecting down from the lower parts of the troughs and smaller ones in the crests of the ridge areas. In the lower parts of the sand in the troughs there are areas of chalky material that appeared isolated in the section (figure 31b), but when excavated back into the face these proved to be cross sections of pseudopods connected to the chalk rubble at the base (see Plate 80). No sign of pseudopods in the base of the sand trough were seen at Grimes Graves. Greater detail of the distribution of relatively clay rich areas and stones at this site can be seen in figure 32.

Voids were present at varying depths between 1.9 m and 2.5 m. Laminations were present in all grades of sand chalk mixture. They were most easily detected in the sandier grades.

<u>Preliminary Interpretation</u>

The greater depth to in situ chalk, the notable concentration of stones at 35-40 cm depth and the paucity of stones above this depth (see figure 32) all suggest that perhaps when the pattern was formed the overall depth of sand was less.

Pipe like features seen in sections by other workers (especially Watt et al 1966) have been suggested to be fossil ice wedges. Clearly these pipes are not, since they have a circular form in plan and there is no disruption of the in situ chalk where they penetrate it. The lack of disruption of the in situ chalk seems to rule out the possibility that they are formed by frost action. The smaller pipe like features seem to cut across other structures of the section. Thus the pipes appear to post date pattern activity. On the other hand the form of the pseudopods in the base of the trough sand, particularly the preservation of thin connections downwards to the chalk rubble, suggests that the troughs have not been markedly enlarged as a whole since the troughs were formed.

During the later discussion particular emphasis will be placed upon the tongue of sand protruding into the base of the ridge form. There was no reason to suspect this was a local peculiarity, but every reason to suggest that this was developed along with the main features of the section. Certainly it was not an 'unusual type of pipe'.

The particularly large amounts of foreign material in the section perhaps also need special mention. Trial excavations in other parts of the general area revealed similar large quantities of foreign material. There are several nearby gravel deposits containing similar material, both at higher and lower elevations. These nearby gravel sections also show cryoturbations and other periglacial features.

5.6 THE DROVE, BRETTENHAM, PATTERN SITE

Surface Form of the Patterns

The location of this site can be seen on figure 48 (Grid reference 914839). Some excellent air photographs of this site (Plate 81) have already been published (Perrin 1963, Williams 1964, Watt et al 1966). This exceptionally good pattern marking was due to sowing of a particularly favourable mixture of grass seed followed by a particularly critical season. Studies of the vegetation of this site have been undertaken by Dr. Coombe of the University of Cambridge. The 'superficial deposits' of this site were mapped as 'Boulder Clay' by the Geological Survey on the most recent map of the area (1882).

On Plate 82 many clear equiforms and elongates can be seen. On Plate 81 indications of equiforms can be seen in the background and clear stripes in the foreground. Between these two areas some very characteristic shapes can be seen. According to the descriptive terminology adopted during the air photograph work (see section 4.2.10 and Appendix F) these would be described as meandroid patterns. It is sufficient to note here that this is a surface expression of the patterns but it does not fully depict the true pattern form.

Form of the Patterns in Section. The excavation at The Drove was generally very similar to the two previously described sites except that it is an excavation across an equiform and the 'buried ridge form' is replaced by a buried flattened dome form on this site (see figures 33, 34, 35). The depth to in situ chalk was difficult to determine but seemed to vary between 2.25 and 2.6 m. Voids were present between 1.6 m and 2.25 m. Voids were present in the bases of many pseudopods. Pseudopods were common but there was no sign of a particularly large pseudopod at the centre. A number of pseudopods showed a two branched form in section that proved to be a trend towards a hemispherical or cup form in three dimensions (see Plate 83). A number of lobate pseudopods were seen in the lower parts of the sand in the infilled trough forms.

Preliminary Interpretation - none.

5.7 SELECTED MINOR SITES

To avoid unnecessary repetition only a selection of field observations from minor sites will be included here to illustrate particular points.

At Babraham a particularly large section through elongates showed that although the patterns were basically similar each individual trough and ridge form varied in size and shape (see figure 36 and Plates 84 and 85). The material in the troughs was rather heavier (more clay rich) than many other sites. This may help to explain why patterns in this area were not particularly well marked on air photographs. Patterns in the soil after ploughing were also noted at this site (see Plate 86).

At Thetford extensive areas of patterning were seen in excavations. Again it was notable that the patterns had overall the same suite of characters but within certain limits there were variations of the form of one pattern section from the next.

At Weeting Heath (Plate 87) equiforms, elongates and stripes were investigated by augering alone (see figure 37). As far as can be determined by augering alone these seem to be the same type of patterns. Augering at the main sites described above gave similar results. Augering at many other sites was often unsuccessful because of the amount of stones present.

At Euston typical pattern sections were seen in a chalk quarry. Particularly well marked patterns were seen nearby, including very regular stripes and exceptionally clear equiforms (Plates 88 and 89). Ground photographs were taken of the stripe site at two different seasons. In one season the patterns showed up well, in the other they did not show at all (see Plates 90 and 91).

5.8 SITES INVESTIGATED BY OTHER WORKERS

Thetford Heath (see Plates 98 and 102).

This site was one of the first described, being a type site of Watt (1955). He described the patterns as stone lines in boulder clay and suggested they were stone stripes. Baden-Powell and West (1960) also described these patterns as stone stripes.

Williams (1964) also worked on this site. Since he was excavating alone by hand he was only able to excavate the sand from the patterns. His excavation demonstrated typical trough forms which he interpreted as sand infilled troughs in 'chalky till'. Other observations included solution modification of the troughs and the presence of stone lines suggesting a pavement of aeolian erosion. He further reported stones projecting from the till "were polished on their projecting surfaces, demonstrating how even the lower layers of sand were wind derived." (Williams 1964 p 339). The observations of the present writer suggest that this last observation was in error.

The present writer did not investigate this site in detail. Brief excavation and augering demonstrated that these patterns were similar to the patterns investigated elsewhere. It seems that the stone lines reported by Watt and Baden-Powell & West were similar in origin to the concentrations of flint in the central dyke form at Grimes Graves. The present writer would describe these patterns as vegetation patterns, though stone patterns are present where the topsoil has been stripped.

Grimes Graves

Williams (1964) also excavated a section at Grimes Graves. Again the section was in the sand alone and only showed the outline of the trough form.

Risby Poor's Heath

Stripes were described at this site by Baden-Powell & West (1960) and Williams (1964). No stripes were seen on air photographs of this locality despite careful examination of several covers. In the quarry section the features at this site were undoubtedly of the same type as the patterns described earlier, though the sand troughs were particularly small. The extremely small size of the sand troughs probably explains why there was not enough vegetation expression to allow the 'stripes' to be detected on air photographs.

Weather Heath

Hodge (Personal Communication) excavated soil pits at Weather Heath which clearly demonstrated deep sand troughs and shallow chalky areas, though he did not excavate a full pattern section. Air photographs of this area (Plate 99) show meandroids. The soil pits and vegetation on the ground suggest equiforms are present.

Investigations by Watt et al (1966)

Watt, West and Perrin investigated a number of sites. Their photographs of Maidscross Hill show involutions, not patterned ground in the generally accepted sense of the word.

Definite patterned ground was investigated at Eriswell High Warren (Pates 93 and 94). The position of the section excavated by Watt et al can be seen on Plate 93, and the published section is reproduced here as figure 38. This section shows sand troughs corresponding to heather stripes. There is a suggestion of a central, large pseudopod and possibly other pseudopods. It is difficult to compare more than the general features of this section with the drawings produced in the present study. The pipe feature at the right hand side of their section is suggested as possibly having originated as an ice wedge. This is very unlikely as their section shows no disruption of the in situ chalk adjacent to the pipe feature.

A further section was excavated by Watt et al in what is described as 'undulating terrain'. Again only involutions appear to have been present at this site.

5.9 SURFACE MARKING OF THE PATTERNS

The most common marking of the patterns is some difference of vegetation, which reflects the soil differences described above. The variations on the two different soil types of the pattern can be differences of species, differences of growth rate or differences of growth form.

Examples of different species being favoured by different areas of the patterns have already been quoted (e.g. at Grimes Graves the natural vegetation of heather and grass is differentiated - see Plate 69). The Drove is an unusual example of differentiated species resulting from cultivation. Two species of grass seed were planted, but each species grew preferentially on a different part of the pattern (see Plate 81). In agricultural areas patterns are more usually marked by differential growth of one species (see Plate 90). Many types of vegetation are affected by the patterns. Cereals near to maturity seem particularly sensitive to the different areas of the pattern. Patterns were also seen in fields of flowering mustard, where one part of the pattern favoured earlier flowering. Well marked patterns seen in fields of beet have been recorded. In this case the clear marking was due to 'Docking Disease' differentially attacking the beet on the more sandy part of the pattern (Brenchly personal communication 1964). One of the most remarkable markings of the patterns was seen in differential tree growth. A number of examples were noted during this study and one of the best is shown in Plate 95. This pattern is in planted trees, but is clearly not following planting lines. Measurement of stripe width gave an average of 7.0 m, standard deviation of 0.9 m and range between 5.3 and 7.9 m - a normal set of stripe data. All afforested sites showing patterns were planted between 1924 and 1929 (Evans, personal communication).

The reasons for the differentiation of vegetation seem to be a moisture factor, a base exchange factor or a pH factor. The chalk both retains moisture better and also maintains a relatively high pH. Base exchange conditions are likely also to be better when chalk is present. On some sites, particularly many of the cultivated sites, the moisture factor seems to be the most important one. Svensson (1966) describes details of the moisture conditions which are responsible for vegetation marking fossil ice wedge polygons in Sweden. Dimbleby (1952) describes apparently similar patterns in Yorkshire, U.K.

In the case of the natural vegetation differentiation between heather and grass pH is almost certainly the dominant factor. In many cases the marking is probably due to a combination of the above mentioned factors, which are in themselves inter-related. Possibly other factors may influence the vegetation reflection of the pattern at times - for instance in the case of the sugar beet disease the texture of the soil seems to be the most important factor. Considerable work on the differentiation of Breckland vegetation on different soils has been carried out by Watt (1936, 1940).

Relatively few patterns are marked by relief differences. An example was seen at Grimes Graves where vehicles travelling over a track had produced relief differences (Plate 96). Many more patterns distinguished by soil colouration were seen (e.g. see Plate 86). These are usually marked by contrast between white and brown colouration in strips after recent ploughing. Since ploughing tends to move the soil it is very doubtful if equiforms could be reliably recognised in plough land.

5.10 AIR PHOTOGRAPH INTERPRETATION OF PATTERNED GROUND IN EAST ANGLIA

Large forms of patterned ground are generally much more easily detected on air photographs than on the ground. Approximately 10,000 air photographs were examined during the present study to produce a map of the patterned ground of East Anglia (see figures 39 and 40 and maps 8-12). The mapping was originally carried out on maps at a scale of 1:25,000 and reduced for other purposes. Sample copies of the original mapping can be seen in figures 43 to 47. Complete coverage of vertical air photographs was used plus an extensive collection of high quality oblique air photographs. Comparison of the records from these two sources suggests that the pattern mapping is reliable (see figure 40). The mapping has certainly not included every patterned area, but it is unlikely that major new areas will be found using air photographs. Williams (1964) produced a map of Great Britain showing patterned ground, including the type of patterning described above. He noted some 500 localities. The general features of his map for East Anglia correspond with the results of the present independent study, with a few omissions (Compare figures 39a and 41). The number of 'localities' mapped during the present study were not counted but some thousands of occurrences were recorded.

Air photographs have a number of advantages and disadvantages when used in a study of patterned ground. Perrin (1963) has written an account of the use of air photographs in the study of patterned ground in Breckland (a summary of his work is given in Appendix F Part 2). An understanding of the interpretations made in the present study can best be gained by reference to Plates 68, 92, and 97 to 107 and the accompanying explanations. It was notable that relatively few equiform localities were observed.

A persistent problem is encountered in classifying some patterns seen on air photographs, even though they are recognised as patterned ground. The present writer has used the term 'meandroid' to describe patterned ground which is difficult to classify on air photographs. Some patterns have appearances on air photographs that do not correspond to the normal classification of patterned ground (see figure 56). Other patterns are so poorly depicted on the photographs that they cannot be classified, though still being recognisable as patterned ground. In the early stages of the study, before the terminology given in section 2.4 was produced, certain patterns were unclassifiable because they were clearly neither 'polygons' nor stripes.

During the examination of the air photographs many minor variations of form and association of the patterns were noted. A representative selection of these can be seen on the photographs included in this thesis. Since few of these variations can be definitely or significantly interpreted the present writer has refrained from attempting to describe these, except where they have some definite bearing on the conclusions of this thesis.

An outline of the methodology of the air photograph interpretation used in this study is given in Appendix F. All the patterns recorded from air photographs are contiguous, probably because grouped or isolate patterns would not be recognisable. A very few possible suggestions of loosely grouped or isolate patterns were seen in some quarry sections.

5.11 PREFERRED ASPECT OF THE PATTERNS AND RELATIONSHIP OF ELONGATION TO SLOPE

Preferred Aspect

Careful examination of the maps of the patterns of East Anglia does not reveal any well marked preferred aspect for pattern development. An attempt was made to produce a more quantitative measure of pattern aspects. Regrettably the reproduceability of the results is in some doubt. (See Figure 93). The data were plotted on an outline map in small units and also grouped in larger units (see figures 93 and 94). The results seem to reflect mainly the predominant local slopes. There seems to be no strongly marked preferred aspect.

Note on the relationship of pattern lineations to slope. Certain observations of pattern lineation noted during the air photo interpretation may be of great importance. Patterns were seen to be lineated at slight but definitely oblique angles to the contours rather than perpendicular to the contours as is usually expected for patterned ground (e.g. see figure 44 Grid References 751231 and 759236). Detailed levelling demonstrated that this angling was present in some cases when it was not suspected from simple observation without instruments. The linear patterns (elongates and stripes) turn in towards drainage channels at sharper angles than they should if following the exact line of maximum slope. They follow lines that sub-surface drainage would be expected to take. Watt et al (1966) also noted that the pattern lineations are not always at right angles to the contours. They suggested that this was due either to map errors or erosion since pattern formation. The consistent natures of the oblique lineations suggests that this cannot be explained as a map error. The amount of erosion needed to account for the obliqueness of the lineations would be many metres in some cases. The presence of patterns across the whole of an area (such as on figure 44) demonstrates that such erosion has not taken place.

The conclusion seems to be that the oblique lineations are real and that they were present when the patterns were formed and active. Oblique lineations of stripes and elongates were seen in both the Seward Peninsula and in Finmark. In East Anglia the oblique lineations are all consistent with a tendency to follow the line of best drainage.

5.12 OTHER PERIGLACIAL FEATURES OF EAST ANGLIA

Fossil ice wedge polygons have been reported in East Anglia by Paterson (1940) near Cambridge. R. B. G. Williams (1964 and 1965) reports a number of fossil ice wedge polygon localities in East Anglia and adjoining regions (see figure 41 and Plate 105).

Involutions are reported as widespread in East Anglia, particularly in chalky deposits (Watt 1955, R.B.G. Williams 1965, Watt et al 1966, West 1968). In most quarries features are present that suggest cryoturbation (see Plate 108). The taele gravels, and other deposits of East Anglia have been interpreted as solifluction deposits. (West 1956, Williams 1964). Williams (1965) suggests that extensive, probably continuous permafrost was present in East Anglia.

Some structures which have not previously been reported were seen at Garboldisham, Norfolk. They were developed in till of apparently Lowestoft age. These are shown in Plate 109 and figure 49 and are described in detail in Appendix B.

5.13 MISCELLANEOUS PERIGLACIAL FEATURES IN THE BRITISH ISLES

During the course of this study many periglacial features in various parts of the British Isles were examined. A number of these the present writer believes have not been recorded previously.

A number of active patterned ground sites were seen near Borrowdale, Cumberland (see Plates 110 and 111).

In a cliff section at Holy Island, Northumberland, cryoturbations were noted (see Plates 112 and 113). The section showed involutions overlain by boulder clay which in turn was overlain by a raised beach deposit. Detailed investigation of this section would probably give useful information for the local chronology.

Some interesting features were seen in a clay band amongst sandy outwash deposits during an excursion organised by the Quaternary Field Study Group (see Plates 114 and 115). Two interpretations of these structures were advanced - cryoturbation and load structures.

Cryoturbation features in shales in County Clare, Eire, were drawn to the attention of the present writer by S.G. Reynolds (University of Bristol)(see Plates 116 and 117). These features are almost certain proof of cryoturbation and include features that would be accepted as ice wedges by most U.K. authorities. This is a particularly important observation since there seems to be no previously recorded evidence of cryoturbation in Western Eire. If some of the features really are fossil ice wedges then the climate indicated would be servere perma-frost conditions (Pewe 1966).

5.14 A NOTE ON THE FROST SUSCEPTIBILITY OF CHALK AND THE DEVELOPMENT OF LAMINATIONS IN CHALKY MATERIAL

The frost susceptibility of chalk is well known to engineers (Ward 1948, Road Research Laboratory 1952, Lewis & Croney ?1965, Higginbottom ?1965). The reasons for this are that the pore spaces in chalk (Black 1953) are the ideal size for development of frost heave as described by Taber (1929, 1930). Ice lenses begin to develop at a freezing front and are supplied readily with moisture from below through the capillaries. The chalk also very frequently has a high moisture content (Lewis and Croney ?1965). When frozen chalk thaws it frequently forms a slurry or 'putty chalk' (Higginbottom ?1965). This is a combined effect of the high moisture content following the thawing of ice lenses and the mechanical properties of shattered chalk (Higginbottom).

Independent observations in the areas around the major excavations across patterned ground are of some interest. After only a single moderate frost the lumps of sand chalk mixture on spoil heaps were found to be frozen with ice lenses inside the lumps well developed, though rather irregular. Unfractured chalk fragments on the other hand developed coatings of ice and no ice lenses inside the lumps. The explanation for the latter observation would seem to be that as the fragments cooled freezing temperatures were reached at the surface of the fragment and a 'skin' of ice developed. This layer would draw the moisture out from the inside, thus developing an ice coating. When all the moisture was exhausted the freezing front would advance into the fragment which would not develop ice lenses inside because the moisture supply had already been exhausted. It was notable that the material in the spoil heaps would appear to be frozen much harder than surrounding vegetation, organic rich soil etc. This is probably because chalk and chalky materials have a high albedo, with the result that they tend to have lower temperatures than surrounding objects. An alternative explanation for the coatings of ice on the chalk fragments might be the deposition of rime on the surfaces of the chalk fragments. However, the appropriate meteorological conditions were not present.

Another observation of considerable interest was the development during the winter of 1964/1965 of laminations in the faces of excavations, parallel to the faces of the pits, to a depth of between 5 and 10 cm.

This observation clearly demonstrated actually on the pattern sites:-

(a) that the laminations are the result of the development of ice lenses,

(b) that the materials are very highly susceptible to the development of ice lenses,

(c) that the ice lenses develop parallel to the freezing front - in this case the vertical faces of the sections.

All three main excavations showed notable frost damage after a single winter.

Watt et al (1966) describe the observation of laminations on the crests of a bomb crater, and in the ejected material. They also describe the development of laminae in "chalk stones ground to a powder, wetted and exposed on the roof of the Botany School (Cambridge) during severe freeze thaw conditions." (p 255). Some emphasis is laid upon the need for severe freeze thaw conditions. Observations by the present writer suggest that the conditions do not need to be particularly severe, nor is more than one freeze thaw cycle needed.

5.15 DISCUSSION OF THE ALLEGED GIPPING TILL ASSOCIATED WITH THE PATTERNED GROUND

A number of possible origins for the materials found in the areas of patterned ground have been proposed. The main disputes centre round the origin of the sand, and the sand chalk mix.

1. Origin of the sand chalk mix as Till, and the sands as decalcified till. The alleged till is generally described as 'Gipping Till' because of its high chalk content (Baden-Powell 1948). Watt (1955) describes the patterns at Thetford Heath as developed in Chalky Boulder Clay. Perrin 1963 describes the patterns as being developed in till of presumed Gipping age. Perrin (1955) came to the conclusion that much of the sand of Breckland was possibly decalcified Gipping Till and published descriptions of the soil forming processes of Breckland based upon the deduction that the sand represented decalcified till (1957). The descriptions of weathered Gipping Boulder Clay given by Baden-Powell (1948 P 285 and summarised in Appendix B.5) bear no resemblance to the sands found associated with the patterns. The paper by Watt, Perrin and West (1966) seems to partly withdraw the earlier separate conclusions of Watt and Perrin, though the material involved in the patterns is referred to as 'till' in parts of the paper.

2. Origin of the Sand Chalk Mix as Till, with the Sand being blown in later. A different sequence was proposed by Williams (1964). He suggested that the underlying material was somewhat variable in origin, sometimes being in situ chalk and sometimes 'Gipping Till'. The proposed sequence of development was that the ridge parts of the patterns developed first (presumably as some form of relief patterns) and the sand polished the flints and (?later) infilled the troughs. It was

suggested that the stones were distributed through the sand by frost action. He states that flints were polished on the surfaces that projected from the till. During the present study the flints distributed throughout the 'till' were found to be commonly wind polished. Unfortunately Williams' sections were in the sand areas of the patterns only, had he been able to excavate further his conclusions may well have been different. For instance he describes the material below the sand at Grimes Graves, including the ridge areas, as 'Chalk' without qualification.

3. <u>Origin of the Sand Chalk mix as an on site mixture of wind blown sand and local chalk</u>. The present writer (1964, 1965) suggested that the sand chalk mixture found in the pattern sections was definitely not till. It was suggested that wind blown sand was mixed by frost action with the local chalk and hence the sand chalk mixture originated on the individual sites. The allochthonous stones were proposed as being already on, or near, the proposed sites. "Some of the sand may have been blown in at the time of formation or later" (Nicholson 1965 p 2). An essentially similar hypothesis was put forward as one possibility by Watt et al (1966).

In detail the arguments in favour of this theory are as follows. Despite the conclusions of Perrin (1955) this study demonstrates the extreme difficulty of determining if the sand had ever contained chalk - and hence could be decalcified 'till'. In brief the chalk would leave no definite evidence following the solution of the calcium carbonate. From the structures remaining in the sand areas there does not 'appear' to have been a lot of general solution since pattern formation, apart from the development of the pipes. This is, however, debatable evidence. The stone fractions of the sand in the troughs and the sand chalk mixture have sufficient in common for it to be fairly certain that the weathered stones of the two areas have a common origin (see figure 89). However, proof that the sand is decalcified, or the sand chalk mixture is sand mixed with local chalk, does not seem to be obtainable from the trough sand areas.

The sand chalk mixture was compared in detail with undoubted Gipping Tills, particularly the Gipping Till at High Lodge. This till has been demonstrated to be Gipping Till by stone orientation (West & Donner 1956) and from associated interstadial deposits (West - personal communication). This till differed from the sand chalk mixture of the pattern sites in the following ways:-

(i) The lithology of the clearly allochthonous erratics included a wide variety of lithologies not found at the pattern sites, including Jurrassic fossils.*

<u>Footnote</u>*. A speciment of <u>Quenstedoceras</u> was found in the till section.

(ii) The flints in the till were fresh and not wind polished or frost spalled.
(iii) The till contains chalk fragments that are obviously striated. No similar chalk fragments were seen at the pattern sites.
(iv) There was no regular variation of the sand:chalk ratio upwards in the section, and in particular no suggestion of the till being sandiest at the base.
(v) The mechanical analyses differ markedly from those of the pattern sites in their very high clay content (see figure 87) and in the much poorer sorting of the sand fraction (the analyses of other Gipping Tills given by Watt et al (1966) also show similar high percentages of clay and poorer sorting of the sand).

Thus the material found at the pattern sites does not resemble proven Gipping Tills. Additionally the material at the pattern sites is of relatively uniform thickness, shows clear signs of frost disturbance and no positive characters whatsoever of a till. The denudation chronology of East Anglia has been long and complex so that there is no problem regarding the presence of allochthonous material, particularly since this is dominantly of the ubiquitous 'Bunter' type, found on many sites that are clearly not underlain by till. If the sand-chalk mix had been produced by an ice sheet moving across a chalk surface then it would be expected to be more chalky at the base, not the reverse situation which is found. Any general decalcification of the till would tend to exaggerate this trend (though little evidence for general decalcification throughout the sand-chalk area is present).

The origin of the sands of Norfolk by aeolian action has long been discussed (e.g. Rastall 1912). The recent paper by Chorley, Stoddart, Haggett and Slaymaker (1966) supports this idea (though, despite comments to the contrary, it is not easy to confidently accept 'best fits' that only explain 21.51% of the observations). The detailed origin of this material, however, remains in doubt. The evidence from the present study does not support Williams (1964) statement that the patterns 'confirm' the periglacial origin of the Breckland Sands, though equally it certainly does not rule out such an origin. It is interesting to note that Black (1951b) reports sands of similar grainsize in dune forms in Alaska. These are presumably derived from glacial outwash under periglacial conditions. Such an origin for the Breckland sands of Norfolk would fit the local chronology very well.

Thus the present writer is firmly of the opinion that the material seen in the pattern sections is not till. This point is of no little significance since extensive areas where the patterns are developed in East Anglia have been mapped by the Geological Survey as till. Some earlier workers have been suspicious of the nature of these 'tills'.

West and Donner avoided using evidence from them because of their peculiar nature (West, personal communication). However, until the present study no systematic assembly of evidence had been carried out. If the conclusions of the present study are accepted then a large number of square miles of 'till' must be re-examined.

5.16 DISTRIBUTION OF PATTERNS IN EAST ANGLIA

The distribution of patterns in East Anglia is shown on figure 39. Williams (1964) map is very similar except for a few omissions (see figure 41). Williams came to the conclusions that the pattern distribution corresponded to the outcrops of chalk. Comparison of figure 39a with figure 39b confirms this conclusion. The western boundary of the patterned ground correlates almost exactly with the western boundary of the chalk. In the southern part of the area, south of Newmarket and Thetford, the limit of patterned ground corresponds to the boundary between chalk outcrops and till. The till of this area is quite distinctive and seems to have been correctly identified by the 19th century Geological Surveyors. Perrin (personal communication) states that the tills of the southern part of the area are much heavier than the tills of northern East Anglia. In the north of the patterned ground area the eastern boundary of the patterned area does not fit the geological drift map distribution very well. In a generalised way patterns decrease eastward as the chalk is buried under an increasingly thick layer of drift. The photo study was not extended outside East Anglia and therefore no comment is offered on possible patterns or lack of patterns outside this area (though see Williams 1964 and figure 41)
In detail the outcrops of 'boulder clay' and other drift deposits marked on the 19th Century maps bear little relationship to the distribution of patterns. This is not surprising since many of the pattern areas have themselves been interpreted as 'Gipping Till'. In some areas the patterns show definite correlations with local drift boundaries on the geological maps, elsewhere there may be no correlation at all with deposits interpreted as being the same. There seems little doubt that parts of the 19th Century geological drift map are so inaccurate as to be useless. Within the main area that is patterned there are a number of areas where patterns are absent (see figure 40). Undoubtedly the large gaps west and north west of Thetford are because the area is forested. The mapping was by air photographs and patterns are only rarely discernible in woodland areas. Certain gaps in the patterns are related to rivers and their associated deposits. There are notable pattern free areas near the rivers Lark and Wissey, and less well marked areas with few patterns near to the rivers Granta and Little Ouse. In the field there are close correlations between the boundaries of pattern areas and areas of gravel and other surface deposits. There seems to be more value in using air photograph observations of pattern sites to

interpret local areas of surface deposits than using the drift marked on the geological maps to interpret the distribution of patterns. Maps 8 to 12 (in the pocket) will probably be of considerable value when the areas is re-mapped geologically.

In summary the patterns are found where chalk outcrops. The western boundary of the patterned area is the western limit of the chalk. The eastern boundary of the pattern area is where the chalk is buried beneath too deep a layer of drift. The Geological Survey drift boundaries are reli able guides to pattern distribution in the southern part of the area, but virtually useless in the north.

5.17 AGE OF THE PATTERNED GROUND OF EAST ANGLIA

The present writer has little to add to the conclusions of Williams (1964). Shotton (1962) suggested that most of the patterns are not earlier than the last glaciation, because of their widespread conformity with the present landscape. The overriding by the ice sheet of the Gipping Glaciation is extremely unlikely to have allowed the preservation of widespread patterning over the landscape. Presumably some patterns could have begun forming in the late Gipping period, following the retreat of the ice.

Patterns occur on river plains interpreted as formed during the last interglacial (Williams 1964 following Sparks 1957). Williams mentions a pattern locality where the troughs are 'infilled' with Taele gravel, and suggests that this means aGipping date of development. If, however, the patterns simply developed in pre-existing deposits then this earlier date proposed is not necessary. If the cover sands of Lincolnshire are not older than Weichsel as suggested by Straw (1963), and if the sands of East Anglia can be correlated with these, this would again suggest a Weichsel age of development of the patterns. The artifact found at Grimes Graves is not of a distinctive typology and the patterned ground will have to be used to date the artifact, rather than vice versa.

The evidence strongly suggests that all the patterns were active during the last glaciation (Weichsel). It seems improbable that most of the patterns originated earlier, though it is likely that occasional areas were.

5.18 SUMMARY OF THE MAIN FEATURES INVESTIGATED IN EAST ANGLIA

The surface form of the patterns is most commonly elongates or stripes with equiforms occurring less frequently. On air photographs the patterns are very easily distinguished though some observations cannot easily be assigned to the classes of equiform, elongate or stripe. The patterns are most commonly marked by vegetation differences, sometimes by soil colour contrast and occasionally by other features. The patterns cover some 2.5% of an area of 1,000 square miles - i.e. one two thousandth of England is completely covered by these patterns.

In section the most obvious features are the sand filled trough forms with ridges of chalky material between. All the patterns overlie in situ chalk at shallow depth. The in situ chalk passes upward into a zone of chalk rubble, which extends across the base of the whole pattern at approximately constant depth.

The buried ridge form is a chalk rich area consisting mainly of sand chalk mixture of varying grades with chalk rubble pseudopods extending upwards from the chalk rubble zone below. The pseudopods vary in form but are generally vertically trending. On slopes the pseudopods are inclined downslope. Sometimes there is a particularly large pseudopod in the centre of the buried ridge form. The sand chalk mix contains most sand near the base and least near to the surface. There is a sharp contact with the chalk rubble zone below and with the lower parts of the pseudopods. In some cases sand from the troughs extends some way across the base of the buried ridge form.

The sand in the infilled trough forms is generally clean sand though there are clay rich areas in all cases, particularly adjacent to chalk areas ('clay shift'). The sand troughs are commonly modified by small pipes extending downwards from them.

There are voids between the chalk rubble fragments in much of the chalk rubble zone. This seems to be an essential feature of all pattern sections. The openness of the voidal area contrasts strongly with the very compact sand chalk mixture and pseudopod areas above. In the sand chalk mixture laminations are common. The laminations are generally sub-parallel to the surface but commonly turn upwards near their contacts with pseudopods.

The stones can be divided into two groups. Firstly the flints that are unweathered except for simple fractures are found dominantly in the in situ chalk (unfractured) and in the chalk rubble of the chalk rubble zone and pseudopods. The second group is the weathered flints and allochthonous stones. The weathered flints may be frost spalled, wind polished, water rounded or apparently solution fretted. The allochthonous stones are dominantly well rounded quartz and quartzite (probably derived Bunter). The stones of the second group are found in the sand troughs and in the sand chalk mixture, but not in the chalk rubble areas.

There are variations from one site to another, and from one pattern to another. The most notable are the variations in pattern dimension and in the relative size of troughs and ridge forms. There are variations in the form, quantity and clarity of the pseudopods*.

Footnote.* Williams (1964) reports patterns developed without any involutions. This does not accord with the observations of the present writer and may be explained by the fact that the excavations by Williams were shallow.

There are also variations in the depth of the pattern, if the depth of either the in situ chalk or the chalk rubble zone is considered.

Thus there seems to be a range of essential characters of the patterns which can vary within certain limits.

5.19 PRELIMINARY INTERPRETATIONS OF THE MECHANISM OF ORIGIN

Evidence of Movement of Materials in the Patterns

1. There is evidence of movement from the base upwards (chalk upheavings and chalk rubble pseudopods). The main movement upwards has been in the ridge areas, particularly in the centres of the ridge areas of some pattern sites (Grimes Graves and Thetford Heath). However some sites also show smaller upward movements into the base of the troughs.
2. There is clear evidence of movement across the base of the patterns from the direction of the troughs towards the centre of the ridge areas (sand lobes, flints at Grimes Graves). Less definite evidence for movement across the base is a universal trend for the sandier grades of sand chalk mixture to be low in the section. This is compatible with either a movement of sand dominantly in from the troughs at the base, or with the pseudopods becoming mixed into the sand chalk mix near to the surface. Possibly both these suggestions are correct.
3. The upper parts of the pseudopods in some cases suggest that near the surface there is movement sideways. Other evidence of movement sideways has possibly been destroyed by agricultural and other human activity.
4. The inclination of pseudopods downslope on slopes demonstrates that as the chalk rubble moved upwards it also moved downslope. There is a maximum of 4 m of downslope movement for 2 m of upward movement, suggesting that the movement downslope, though definite, is not a 'fast' movement. This supports the work of Williams (1964) who points out that stripes can pass downslope into equiforms which strongly suggests that no 'massive solifluction' has taken place (see Plate 118).

Evidence of the Mechanism of Development of the Pattern

There are obvious broad similarities between these patterns and certain patterns in periglacial areas. Chalk is known to be specially susceptible to frost action, sand is relatively non susceptible. Evidence has been presented that the laminations seen in the patterns were produced by ice lenses. Other evidence has been presented for the migration of moisture from the centres of pieces of homogenous pure chalk outwards to developing ice crystals. The laminations were seen in the the sand chalk mix but only in the smallest pseudopods. The voids in the chalk rubble contrast strongly with the compact sand chalk mix above.

Deductions as to certain aspects of the Mechanism

1. Major heaving forces were produced by the development of ice lenses.

2. The chalk rubble voids were ice filled during the time of development of the major heaving pressure otherwise they could not have survived in their present form.
3. If major heaving was developed in the chalk rubble zone and if the voids were ice filled when the heaving pressures were developed, then this means an unfrozen layer overlay a frozen material. This necessarily means that frozen ground lasted throughout the year whilst the zone above thawed in the summer season, i.e. permafrost was present.
4. All periglacial patterned ground develops not only because of frost action, but also because the frost action acts in some way differentially. In this case it is almost certain that the differential action was between sand trough areas and chalk rubble areas. Possibly peat was also present, acting in some way to produce differential frost action, likewise possibly differential vegetation cover was present. In the strongly oxidising environment of the patterns it is not surprising that neither peat nor ancient vegetation have survived, if they were ever present. The lobes of pure sand penetrating the base of the patterns on certain sites demonstrates that pure sand was present when the patterns were active, with or without organic matter. The structures at Garboldisham are so similar to structures in peat in Alaska (compare Plates 27 and 109) that it is tempting to regard this as evidence that pure sand in East Anglia could have acted in the same role as peat in active patterns in Alaska. Possibly peat was originally mixed with the pure sand.
5. Since the chalk rubble pseudopods have clearly been moved upwards from below this demonstrates that the chalk rubble zone was not frozen throughout the whole time of the development of the pattern sections as seen at present.
6. Much of the 'movement' evidence suggests a circulation movement of the same form as convection currents. The weak evidence for a movement outwards at the surface does not contradict this since any such evidence that might have been present would be in the zone of human disturbance. The evenness of the chalk rubble mixture may suggest continuous 'stirring', but the contrasting materials evidencing the 'circulation' suggests different factors may have acted in different areas of the pattern.
7. Despite the evidence for a 'circulation' and almost indisputable evidence for movement across the base, the movement upwards of many of the pseudopods is clearly across this movement. There seems to be a main pattern of troughs and ridge forms, with upward movements superimposed. This distribution, and particularly the pseudopods in the base of some sand troughs, may well suggest a two stage mechanism is needed to produce the full suite of features seen in the sections.

STUDIES IN NORTHERN SCANDINAVIA

6.1 INTRODUCTION

The main studies were carried out in Finnmark. Finnmark is the most northerly province of Norway, and hence is the most northerly land area of Europe.

The Scandinavian ice sheet was the largest source of ice for North West Europe during the glaciations. Thus it is not surprising that within the main accumulation area of this ice sheet the Pleistocene record is much briefer than in the two areas previously discussed. The main evidence in the area is of retreat stages of the last glaciation and only very fragmentary evidence of earlier Pleistocene events is present in Central and Northern Scandinavia. A notable feature of the Scandinavian ice sheet was that at its maximum development the greatest thickness was not over the mountains of Norway and Sweden but over the Gulf of Bothnia. This had important effects on the isostatic recovery that has accompanied the melting of the ice. The isostatic recovery is well recorded in the raised beaches of Scandinavia. The general stages of the retreat of the Scandinavian ice sheet were dated by De Geer (1912) during his classic varve studies.

6.2 THE GENERAL GEOMORPHOLOGY OF FINNMARK

The Finnmarksvidda is a plateau area covering much of Finnmark south of the coast. The plateau varies in height from 400 to 1,000 m, generally declining in height southwards and eastwards towards Finland. This area was traversed by great quantities of ice during the last glaciation. The result is a rolling landscape with predominating bare ice eroded rock in some areas and deposition in other areas, and many lakes. Drumlins and eskers are extremely well developed in some parts of this area (Holtedahl 1960). The present writer saw some fairly extensive areas of dead ice forms, though comments by Holtedahl suggest that these are not common throughout Finnmarksvidda. In major valleys the most striking feature is the enormous quantities of out wash deposits e.g. in the Altaelva (valley). The coastline is fjorded, though the fjords are not as spectacular as in Southern Norway. A variety of glacial erosion and deposition forms are found with raised shoreline features superimposed (see Plate 119). Dahl (1955) has suggested that some fringe areas may never have been ice covered, but this idea is strongly disputed by Holtedahl (1960).

6.3 OUTLINE OF THE GLACIAL CHRONOLOGY OF FINNMARK

The chronology in Finnmark rests largely on the evidence from raised shorelines. Virtually all of Finnmark was certainly covered by ice. The suggestion by some authors that Magerøy remained ice free is discussed below, though the present writer concludes that this suggestion is unlikely to be correct. The fjord coast of Finnmark was the site of the classic raised shoreline studies of Bravais (1838 referred to in

Marthinussen 1960) and Tanner (1930). The thickest part of the ice sheet lay south of Finnmark, and hence the greatest isostatic recovery is to the south, or landwards, in Finnmark. This means that a raised beach of a certain age will be lowest on the islands and near the mouths of fjords and highest at the landward (southern) ends of the fjords. To add to the difficulties of correlations of the beaches there has also been progressive rise of sea level, and additionally the oldest beaches are present only in the seaward parts of the fjords as the ice was still present in the southerly parts.

A large number of shorelines have been identified. Marthinussen (1960) divides a total of 39 shorelines into three series - S or Late Glacial (sen-glacial), P or Post Glacial, N or Neo-Glacial. Dating is from several lines of evidence. The Late Glacial to Post Glacial transition is identified by the relations of a particularly well marked raised shoreline to major moraines which can be correlated with the Ra substage of Southern Norway (i.e. end of Gotiglacial). Dates for the 'N' shorelines of Marthinussen have been obtained from C14 dating of peat deposits overlain by beach material and from drift wood. Pumice incorporated in beach deposits in this area has been used for dating. This latter evidence is controversial, but fortunately does not affect the present thesis.

Recent studies by Hoppe (1959 and 1961) for inland Northern Sweden suggest that deglaciation of inland areas was between 7,000 and 5,000 B.C. (9,000 to 7,000 B.P.). In Finnmark shoreline studies show that ice was present at the fjord heads at 10,000 B.P.

6.4 PREVIOUS STUDIES OF PERIGLACIAL FEATURES IN SCANDINAVIA

This section is limited by the fact that the researcher does not read Scandinavian languages, but it is thought that the summary presented is representative, even if not complete.

The review of periglacial studies in Scandinavia by Rapp and Rudberg (1964) mentions many reports of both active and fossil patterned ground. Since this review was published there have been further studies undertaken (e.g. Svensson 1967, Kallander 1967, Maack 1967, Ohrngren 1967). Some of the more important studies in Scandinavia have been studies of stone orientation associated with patterned ground and allied features (e.g. Lundqvist 1949, Maack 1967); studies of the climatic limits of active patterned ground (Williams 1961, Sollid, referred to in Rapp and Rudberg 1964) and studies of the tracing of patterns using air photographs (especially Svensson 1963, 1964b, 1967). Most of the Scandinavian studies have been directed towards patterns of possible ice wedge polygon type, forms grading from solifluction to patterned ground and forms of patterned ground of 1 to 2 metres or smaller. Relatively little attention has been paid to large forms of patterned ground that do not appear to be ice wedge polygons.

Some authors include parts of Finnmark in the permafrost zone (e.g. Black 1950), others exclude Finnmark (e.g. Muller 1947). Rapp and Rudberg (1964) mention small areas of permafrost in particularly favourable localities (associated with peat and bogs). Annersten (1966) reports permafrost in the Padgelanta area, height 760 m in North West Sweden, proved by long term ground temperature measurements. Study of the results from Alaska indicated that the development of the large patterns required permafrost conditions and probably rigorous permafrost conditions rather than marginal permafrost conditions. Thus the Finnmark area was thought to be too warm for large patterns to be fully active, though some semi-active fossil patterns were expected. Reports by Lundqvist (1949) and C. High (personal communication) suggested that some large patterns were present in addition to the probable ice wedge patterns reported by Svensson.

6.5 AIMS OF THE WORK IN SCANDINAVIA

The studies in Finnmark were undertaken for several reasons. Firstly to confirm that large patterns are not active under the marginal permafrost conditions of the area. Secondly to see what patterns, or range of patterns do appear to be in balance with the present climate. Thirdly to examine the structures of the patterns observed to obtain further information bearing upon the origin of patterns in general and large patterns in particular.

The work in Finnmark was much less comprehensive than the work in either Alaska or the United Kingdom. The work was based upon a relatively small number of sites and especially a relatively small percentage of air photo cover. As a result it is less easy to generalise about the patterns of Finnmark.

6.6 DESCRIPTION OF THE PATTERNED GROUND OBSERVED IN FINNMARK

The patterns which occurred most commonly and were most regular were relief patterns of stripes or equiforms some 1.5 to 2 metres across (see plates 137-140). This group of patterns were referred to by the present writer as the medium sized relief patterns of Finnmark. These relief patterns are not the same as peat hummocks described from many arctic areas since they become elongated on slopes of a few degrees, whereas peat hummocks remain equiform even on fairly steep slopes. There were notable variations of the structure of these patterns in section, as shown in figures 68-70 and Plate 140. The ring ridge features mentioned by Svensson (1964a p 105) were frequently observed in the same areas as the medium sized relief patterns, perhaps suggesting some relationship. There is a superficial similarity of appearance, though the ring ridges can be notably larger. The relationship could be a very loose one as in the relationship between solifluction lobes and relief elongates which are commonly found together on Magerøy (see also Kallendar 1967). Full discussion of the common, medium sized, contiguous relief patterns of Finnmark will be deferred until after the general discussion of pattern formation in all regions.

At one locality relief equiforms of about the same size were seen which showed no elongation even on fairly steep slopes (see Plate 136). These patterns differed in their steepness of relief, in being isolate and in showing a greater variety of size. These do not appear to be the same sort of feature as the medium sized relief patterns and are probably similar to the hummocks described from other arctic areas (Washburn 1956, Smith 1961).

A variety of large patterns were seen at a relatively small number of localities. None were exactly like the patterns seen in either the Seward Peninsula, Alaska or East Anglia, Britain.

'Large' patterns were seen particularly on the Finnmarksvidda, but also in some other localities, with stripe widths of 3.5 to 5 m and equiform diameters of 4 to 6.5 m. Plates 122 and 124 are typical examples of the surface form and Plate 123 and figures 52, 53, 55 show details of form and section. Study of the pattern form on the ground and on the air photographs of this site clearly demonstrated why the 'meandroid' type of patterning is observed on air photos when there are equiforms or elongates on the ground (see figure 56). The patterns often had bare earth patches (frost scars) subdividing the central areas, or randomly scattered. Even the most active do not suggest sufficient activity for development of new patterns and are probably only 'ticking over'. Some features of the heat flux in this type of pattern were demonstrated by the differential snow melt on frost scars (see Plate 125). In some cases the 'large' stripes were seen to be dividing into separate medium sized relief stripes which were similar in section to the medium sized relief patterns seen on Magerøy (see figure 54). On one site there was a hint that the 'large' patterns were themselves the divided parts of even larger patterns (presumably 7 m wide - see figure 55).

On moderately steep slopes in the Sennelandet Valley, north east of Alta, solifluction lobes and vague patterning were observed in oblique lineations across slope. Kallendar (1967) and earlier authors have described similar lineations obliquely across slope on Magerøy which have not yet been explained. In the Sennelandet Valley the lineations were clearly parallel to oblique rock outcrops marking the bedding of the rock or some other bedrock weakness. There seems little doubt that in the Sennelandet valley the oblique lineations are related to the underlying rock structure.

On the western coast of Porsanger Fjord, large apparently active frost scars several metres across were seen (see Plate 135). On Kistrandfjell, in the same general area, very active looking large patterns were marked dominantly by vegetation and frost scars (see

Plates 126 to 132 and figures 57-63). These patterns were most remarkable in the relationship between elongation and slope. Patterns were elongated in trains downslope, in trains obliquely across slope and also parallel to the contours (see figure 57). The lineations downslope and obliquely across slope might be termed either elongates or stripes. The centres of the lineations were made up of many frost scars in trains, rather than continuous bare soil (see figures 58 and 63). The lineations across slope could be described as steps (see figure 62). The remarkable lineation of patterns in relation to slope at Kistrandfjell requires further comment. In places the disparity between stripe like lineations and slope was as much as 30° or more. This is certainly not usual in patterned ground areas, though some disparity between slope direction and elongation direction has been noted previously (see sections 4.2.1. and 5.11).

The location and form of at least some of the steps at the nearby site of Billefjordfjell is primarily related to bedrock at shallow depth (Plates 133 and 134 and figures 64 and 65). Troll (1944) has noted that patterns may be developed in regions equatorwards of the normal climatic limits due to the intensification of frost heave over bedrock at shallow depth, due perhaps to the rock acting in the same role as permafrost. Linear scars near the summit of Billefjordfjell were noted which were elongated parallel to the contours on a northerly aspect and perpendicular to the contours on a westerly aspect within 25 m (see figure 66). These linear scars are parallel to local bedrock features and within a few hundred metres of the above mentioned bedrock controlled steps, so that the lineations of the scars are probably also controlled by bedrock features below.

The bedrock form and mineral soil at Billefjordfjell and Kistrandfjell are similar, and hence it is reasonable to consider bedrock control at the latter locality. There are east-west solid rock steps at Kistrandfjell that seem to be the result of glacial plucking on some bedrock weakness. The actual pattern sites are covered by mineral soil and peat seen to be at least 1.3 m deep in the sections. The presence of bedrock outcrops in the pattern areas suggests that the mineral soil is generally not very deep. The elongation of the pattern forms accords closely with the east-west bedrock steps. This relationship can be easily seen on the air photographs and was especially obvious on the ground. The evidence from the Billefjordfjell and Sennelandet sites suggests that this accordance of elongation with bedrock features is not accidental. The significance of these oblique lineations will be discussed in detail later.

There was no doubt at all that most of the patterns seen at Kistrandfjell and Billefjordfjell were active. Stones and boulders were common in all parts of the patterns at Kistrandfjell but most abundant beneath the margins. There was sufficient concentration of stones under the margins to strongly suggest sorting, though the patterns were primarily marked by vegetation and hence should have been classified by Washburn (1950, 1956) as 'non sorted'. There was abundant evidence of larger stones being lifted vertically out of the ground at this site. Another notable feature of the large patterns at Kistrandfjell was that the stones were orientated perpendicular to the fronts of steplike features and not parallel to the fronts as in the case of solifluction lobes (See Plate 131 and figure 61).

A very different type of large pattern was seen at Ytre Garadak. These patterns were all aligned north to south (see Plates 141 and 142). They were well developed on south facing slopes and the same lineations continued onto cols and a short way down the north facing slopes. On east facing slopes the lineations were still aligned north to south and the lineations went across slope, ignoring minor variations of relief in a fashion not seen at any other site during the course of the study. The site was a raised sloping beach only 15 to 40 m above the level of the nearby fjord. Rounded beach pebbles and finer interstitial gravel and sand were the main materials seen in sections. The material was clearly not frost susceptible and the 'structures' of sections seemed to reflect soil development under undisturbed conditions rather than any 'pattern forming process' (see Plate 143 and figure 71). There were a few small concentrations of fines on top of some large stones in the section which might suggest that more fines had been present in the past. An interesting observation was that the lichen covered areas are in part maintained by modern reindeer grazing, which disturbs the vegetation and thus presumably helps to prevent higher plants from colonising the lichen areas. The birch plants showed considerable modification of form due to wind, being strongly inclined towards the north. The bushes were stunted on the southern sides and more vigorous on their northern sides. The distribution of birch areas was as if they were the centres of the pattern - which contrasts with all other sites seen, where vigorous birch growth is limited to the margins. These patterns were thought to be determined in their elongation by the prevailing wind. This interpretation was almost certainly confirmed in a minor valley by a change in the alignment of the patterns to a direction coincident with the local prevailing wind, as modified by the valley form.

These patterns were below the P12 shore line (earliest Post Glacial) in Porsanger Fjord as interpreted by Marthinussen (1960) and therefore must have been initiated later than this. The 'Main Line' or P12 shore line is interpreted by Marthinussen (1960) as being at 50 m at Russenes and approximately 55 m at Ytre Garadak site. These patterns were within 20 m of the present Sea Level. If the uplift in this area was similar to the uplift of West Finnmark then this would mean that at least some of the site has only emerged during the Neoglacial i.e. some of these patterns have developed entirely within the last 8,000 years. Precise levelling at this site could easily give a more precise date and in fact some of these patterns could have been initiated much more recently.

Smaller patterns, width about 50 cm were also seen at Ytre Garadak (see Plate 144). Surprisingly these patterns also showed evidence of materials moving from the margins downwards and across under the centres (see Plate 145 and figure 73). Very small patterns, width 15-20 cms were also observed. 3 to 5 m stone equiforms with cobble sized stone borders were observed at two locations. In borrow pits small ice wedge casts and involutions were seen.

6.7 GENERAL NOTE ON PATTERNS SEEN ON AIR PHOTOGRAPHS

Only a sample coverage of air photographs for Finnmark was examined. The most extensive patterning was observed on parts of the main plateau of Finnmarksvidda, such as seen on plate 120. Generally relatively few patterns were seen compared to either the Alaskan or the East Anglian area. This was almost certainly due in part to the fact that the commonest form of patterning (about 1.5 to 2.5 m width) would not be easily detectable at the scale and quality of most of the prints used. It is notable that all of the 'large' pattern sites were located from air photographs, whereas all except one of the other sites were first identified on the ground.

6.8 SUMMARY

The medium sized (1.5 to 2.5 m) patterns were the most common and appeared to be most in balance with the present climate. A variety of large patterns were seen, though none were very common. The most frequent were about 4 to 6.5 m equiforms and 3.5 to 5 m stripes, but these usually appeared notably degenerate and sometimes were dividing to become medium sized patterns. Large patterns were seen that were elongated parallel to rock structures rather than perpendicular to the contours. On one site large patterns were thought to be determined in form by the wind. A variety of other patterns were observed in small numbers.

EVALUATION OF EVIDENCE ON THE GENERAL ORIGIN, DEVELOPMENT AND PERPETUATION OF PATTERNED GROUND

The present research has involved study of many features and deductions can be made from the evidence obtained. However it has only been possible in a few cases to provide anything like reasonable proof of deductions. This may be inevitable at this stage of the knowledge of patterned ground and indeed of many aspects of geomorphology. In consequence of the lack of proof it is desirable to make most of the deductions independent rather than interdependent. This will entail some repetition but it is hoped that it will allow future workers ~~to~~ more easily to identify useful evidence and its significance and (probably more important) that future workers will be able to more quickly dispose of those hypotheses that do not stand the test of time.

7.1 PATTERNED GROUND IS NOT AN EXTRAORDINARY NATURAL PHENOMENON

The most striking feature of patterned ground is, obviously, the pattern. Many texts and detailed papers discussing patterned ground tend to give the impression that a regular patterning is an unusual feature in nature and thus patterned ground seems to stand as an anomalous morphological feature, in contrast to the 'normal' more random natural features. This is far from being true. Where conditions are reasonably uniform, similar sized and spaced features are common. Drumlins, terracettes, meanders and sand dunes are all examples of features that can be regularly spaced - i.e. form a regular pattern. The work of Horton (1945) and others following him develops the idea of regularity of features resulting from water when conditions are sufficiently uniform. Adjacent major mountain ranges, ocean deeps and similar major features are more often noted for their variation than their similarities. This is probably because over very large areas of the earth's surface conditions are rarely uniform. If, however, one moves on to the broader scale of celestial bodies the similarity and regularity of natural forms is more striking than the variations. Thus patterned ground is by no means an exceptional feature simply because there are regular, repetitive forms.

7.2 FACTORS DEVELOPING OR PERPETUATING PATTERNS ONCE THE PATTERN IS ESTABLISHED

7.2.1. Some general Considerations

It will be recalled from section 3.5 that freezing can act in a number of ways to produce movements. Once a pattern has become established with some differentiation further development or perpetuation can follow.

Differential dilation alone could produce vegetation patterns without net movement of the materials (see figure 75a). Differential ice lens development in different parts of the pattern is likely to produce variations of relief at the surface which will cause or facilitate other movements (see figure 75b). Differential development of ice lenses in different materials locally in the pattern can move the materials concerned relative to one another, the movement being either solely vertical or with a variable horizontal component (figure 75c). Varying rates of penetration of freezing temperatures will produce either differential ice lens growth (with the consequences as indicated above) or will produce an inclined freezing front, or both. An inclined freezing front will produce heaving forces which are not normal to the surface and hence movements will most likely not be fully reversed when the ground thaws (see figure 75d). An inclined freezing front will also give opportunity for differential migration of particles at a freezing front with a horizontal component, which can also help to develop or perpetuate the pattern. Initial differentiation of the pattern is also likely to affect the processes which do not primarily involve freezing (see figure 75b).

Thus once a pattern has been initiated and some differentiation has occurred there is a very considerable likelihood of the development continuing or at least the pattern being perpetuated. Many students of patterned ground have focused their attention on explaining how the movements occur given the differentiation they observe in developed patterns and this has then been confused with theories of pattern initiation. The explanation of continuing development of patterned ground once it has been initiated is much easier to understand than the pattern initiation and therefore this topic will be discussed first. Some of the movements are probably similar to the initiating movements, others can only operate after the pattern has been established.

7.2.2 Effects of Differentiation of Materials

Differentiation of materials can cause development or perpetuation of a pattern in a number of ways. Contrasting materials will have different porosities and hence lead to differential Taber ice development. As shown above differential heave will often lead to development or perpetuation of patterns. A common example is the contrast between silt which produces Taber ice very readily and peat which does not allow development of Taber ice. Another example is the ready development of Taber ice lenses in chalky materials and the lack of Taber ice development in sand. Presumably differences of porosity could also affect segregation of ice being fed by water reaching the crystals as a result of external forces.

Different materials will usually have different thermal conductivities which can lead to differential frost heave due to differences in rate of frost penetration. A good example is the presence of a stone border leading to faster penetration of the freezing temperatures, which naturally produces an inclined freezing front. A difference of materials may lead to differential thaw, particularly important in permafrost regions. Greater depths of active layer will be much more liable to develop large amounts of heave. The fact that peat commonly induces a lower temperature regime in the ground can also lead to differential heave when peat and some other material are already distributed unevenly in the pattern. It is perhaps worth remembering that thermal conductivities can be radically altered by freezing, so that most rapid advance of freezing temperatures may or may not be where there was most rapid advance of thawing during the summer season.

Some materials may be mechanically stronger than others and thus resist frost heave more than other materials, leading in turn to differential heave. Hopkins and Sigafoos (1951) suggest that soil with plant roots can resist heave and hence lead to differential frost heave. Although there are no quantitative data available the present writer doubts that the strength of roots of tundra plants is significant compared to the pressures indicated by laboratory and field studies of frost heaving. Another possibility is that some materials are more plastic than others and hence 'flow' more than others when under pressure in the unfrozen state. There is little evidence to suggest whether peat or silt will flow more easily under these conditions, though peat will stand for a moderate length of time in excavations whereas silt very quickly flows into excavations unless it is in an unusually dry condition.

In summary there are a large number of ways that different materials may cause development of patterns once they have been initiated. The most important seem to be in relation to differences of susceptibility to Taber ice segregation and differences of thermal conductivities.

7.2.3 Effects of Differentiation of Vegetation

The effects of vegetation are relatively simple. The vegetation acts as an insulating layer and hence the more vegetation there is the more slowly heat enters and leaves the ground. Alternatively bare ground leads to faster heat loss in winter and greater thaw of permafrost in summer. Effects of some vegetation can be more complex. Dwarf birch and willow considerably reduce the heat gain in summer by their insulating effect. In autumn they lose their leaves and their insulating effect in winter is markedly reduced. Thus some vegetation can induce a lower temperature regime and therefore almost certainly produce a shallower active layer. As an example of cumulative pattern differentiation it is interesting to note that a shallower active layer is likely to lead to less frost heave and therefore more stable rooting conditions. This in turn may allow differential development of peat which will tend to reinforce the lower temperature regime and also itself be less frost susceptible. In contrast to willow and dwarf birch, some plants are not markedly reduced in their insulation effects in winter - notably cottongrass tussocks and lichens. Hopkins and Sigafoos (1951) record how mineral soil is heaved into the bases of cottongrass tussocks, because the ground under the tussocks remains unfrozen when freezing pressures are developed in the ground around them. Another possible consequence of segregation of vegetation is differential action of caribou, moose and reindeer etc. grazing selectively on one species.

7.2.4. Effects of Differentiated Snow Cover

When snow is present it also acts as an insulating layer. If the snow cover lies differentially on the pattern this will promote differential frost heave and hence continued development of the patterns. Hopkins and Sigafoos (1951) suggest that in the case of tussock-birch-heath polygons the snow would lie on the central tussock areas rather than on the higher vegetation tops surrounding. In Scandinavia snow was observed to quickly melt on the pattern centres (possibly combined with differential pitching) and to lie without melting on the vegetation covered borders (Plate 125). Possibly the effects may vary from site to site and from year to year. Some apparently contradictory evidence for movements reported from some sections might be explained in terms of variations of snow cover from year to year.

7.2.5. Effects of Differences of Relief

Differences of relief will cause varied microclimatic exposure and hence plants may become differentiated. On the raised areas formation of frost scars will be encouraged, especially if there are also dilation cracks to aid initiation. Differences of relief could encourage differential snow cover which would add to the above effects, and also cause differential penetration of freezing temperatures. Differences of relief would encourage greater heat loss from the raised areas simply because the radiation would be optimised by the form, though the effects of this may be negligible. Possibly the most important effects of differences of relief is that they naturally lead to inclined freezing fronts which will usually aid development or perpetuation in a number of ways.

7.2.6. Effects of Uneven Moisture Distribution

There is conflicting evidence on this factor. Some workers report more moisture in the centres of patterns and some report more in the margins. Possibly moisture is more abundantly available in permafrost areas in the basins in the permafrost table. There seems little doubt that differential moisture distribution would promote differential heave, both by its controlling the amount of ice developed and also by its effect on thermal conductivities.

7.2.7. Effects of Differences of Depth to Permafrost

The differences of moisture content that can result from basins in the permafrost table has been mentioned above. Another effect is that the greater depth of thawed material will allow greater development of heaving if all other factors are even. Variations in depth to permafrost table must mean that the permafrost table has an inclined front in places. If there is any upfreezing this would have important effects on horizontal components of heaving and movements. There are no data available on the possible effects of differences of frost table depth on heat conduction downwards.

7.3. DIRECT EVIDENCE OF MECHANISMS INVOLVED IN THE PATTERN DEVELOPMENT

7.3.1. Ice Lenses

In the Seward Peninsula ice lenses were seen to be present in suitable materials whenever frozen material was excavated from patterns. These lenses were in the typical 'ice gneiss' form of Taber ice segregations. Regular ice lenses were absent from frozen peat though interstitial ice in the peat was fairly abundant. Laminations were seen in the patterns of East Anglia. Winter observations demonstrated that ice lenses develop readily in chalky material and on thawing leave laminations to record their former presence. The relationships of ice lens casts (laminations) to the surface and to chalk rubble pseudopods has already been noted (see figure 29). The orientation of ice lenses in Alaskan excavations was not noted in detail, though the main lens development was seen to be very generally parallel to the surface. Ice lenses were not observed in Scandinavia, but this is not surprising since the excavations were late in the thaw season and no clearly frozen material was excavated. The materials were not suitable for preservation of laminations. It is notable that all the patterns studied contained material that was clearly susceptible to the development of Taber Ice segregations.

7.3.2 Obvious Frost Scars

Obvious frost scars were present on many active pattern sites. Undoubtedly once they are present they will greatly affect pattern development. (Hopkins and Sigafoos 1951). However it is difficult to interpret whether they are primary or secondary features. Some are undoubtedly secondary, being developed amongst sparser vegetation of well established patterns. This does not mean that the patterns did not originate by frost scar development since colonisation of frost scars followed by renewed development of frost scars seems to be a common feature of many tundra areas (Raup 1951, Benninghoff 1952).

7.3.3 Decrease in Height of Patterns during the Thaw Season

In the Seward Peninsula pattern centres are commonly raised in the early part of the thaw season, presumably the result of the previous winter freezing cycle. During the course of the thaw season the centres become less markedly raised and some become virtually flat. Raised centres at the end of the winter which become less markedly high as the ground thaws have been reported from many areas and pattern types. It is possible that this raising represents material which has been moved into the centres during the winter season and then moves back during the thaw season, but this is very unlikely. It is almost certain that this têmporary raising can be directly interpreted as indicating that there is greater growth of ice segregations under the pattern centres.

7.3.4 Form of Frost Tables

Whenever conditions were suitable for observations frost tables in all relief and vegetation patterns in the Seward Peninsula were seen to be deeper under the centres than under the margins. Where there were indications of the position of the permäfrost table this showed a similar relationship, as was confirmed by augering at the end of the thaw season. Other workers have noted a similar relationship (Elton 1927, Fitzpatrick 1960). There are relatively few observations of depth of frost table under stone patterns. The data of Schmertmann and Taylor (1965) suggest there is little or no difference in active layer depth across stone patterns on their investigation sites.

7.3.5 Heaving of Stones Out of the Ground

Both in Finnmark and the Seward Peninsula large and medium sized stones were seen that were in the process of being ejected from the ground. This clearly indicates the action of some type of sorting process (or processes). In some cases the force of the process of ejection of stones was enough to break through a thin cover of vegetation (Plate 37). Lichen free stones in pattern margins also indicated recently active sorting processes (see Plate 43).

7.3.6 Action of Large Mammals on Patterned Ground

In Scandinavia reindeer were seen to be preferentially grazing on the lichen of pattern centres. Their grazing and trampling was having considerable effects on the stability of the vegetation and presumably upon the establishment of frost scars. Hopkins (personal communication) reports widespread vegetation damage and trampling in the patterned ground areas around Imuruk Lake following the passage of grazing herds.

7.4 IMPORTANT INDIRECT EVIDENCE OF MECHANISMS

All the evidence considered in the section above entitled "Factors developing or perpetuating patterns once the pattern is established" should be taken as included here. Definite evidence of movement of materials will be discussed separately in the section following this one.

7.4.1 The Presence of a Voidal Layer and the Possible Importance of Upfreezing

The work of Schmertmann and Taylor (1965) clearly demonstrates that in the patterns studied by them much of the heave was developed by upfreezing (see figure 76). Upfreezing in connection with patterned ground has been suggested by a number of authors (Meinardus 1930, Poser 1933, Black 1951a, Schenck 1955, as quoted by Washburn 1956 p 842). Washburn suggests that the 'zero curtain' and 'thermal regime' work described by Muller (1947) "throw doubt on the importance of freezing from below" (Washburn p 842).

It is very difficult to understand how Washburn interpreted Muller to reach this conclusion. It seems possible that Washburn may have interpreted a slow advance of the freezing front consequent upon development of much segregated ice as meaning that upheaving would be unimportant. As demonstrated by Schmertmann and Taylor, slow advance of freezing front with the same temperature gradient is an indicator of greater rather than less heave. To develop a zero curtain effect there must be water freezing to become ice and hence development of pressure is a natural consequence of marked zero curtain zones. An important point to note is that upfreezing pressure depends on moisture available to move downwards and the temperature of the main permafrost mass. Upfreezing pressure can be completely independent of 'frost susceptibility'.

A voidal layer across the base of patterns was present in all East Anglian sections examined. Poorly marked voidal zones were seen in several pattern sections in the Seward Peninsula where materials were suitable. The common absence of a voidal layer in thawed ground is to be expected since wet thawed silt would tend to infill any voids. It seems most likely that these 'voidal' areas are the result of concentrations of ice segregated due to upfreezing. It is particularly difficult to believe that voids at the base of patterns could have been open when the main heaving pressures were developed. If the voids described above are evidence of upfreezing then upfreezing must be considered an important element of the development of patterns both in East Anglia and the Seward Peninsula. Proof of this suggestion would also have important implications concerning the climatic conditions of development of the patterns of East Anglia.

7.4.2 Pattern Lineations Not Parallel to the Slope

In East Anglia quite a large number of patterns were seen that were not lineated parallel to the steepest slope (see section 5.11). The only explanation acceptable in all cases is that these stripes and elongates are parallel to the drainage. When favourable lines of drainage, particularly minor watercourses, are present across a uniformly sloping hillside then water will tend to drain towards the watercourses at an angle to the maximum slope. A similar situation occurs when drainage is installed on farmland. The artificial drainage lines modify the local direction of drainage so that it is not exactly parallel to the steepest slope.

On one site in the Seward Peninsula lineated patterns were also angled away from the direction of maximum slope. Lineation parallel to the lines of drainage is again the most satisfactory explanation. No other similar observations were made, but the nature of the work and instruments used meant that only the most obvious cases would be noticed.

In Scandinavia at Kistrandfjell patterns lineated at very large angles to the maximum slope were seen (see figure 57). These were parallel to local bedrock lineations, though the bedrock was more than 1.5 m deep in two sections excavated. The angled lineations could be caused by a direct bedrock control of some pattern forming process, or the rock lineations may control drainage directions and the drainage controls the pattern lineation. Solifluction lobes in lineations across slopes have been reported on Magerøy by Kallendar (1967) and others. In the Sennelandet Valley lineations of poorly developed patterns and solifluction lobe like forms were seen parallel to bedrock lineations, at an angle of more than 20 degrees to the maximum slope. In this case again either direct bedrock control or indirect control by control of drainage lines is possible. In the case of solifluction lobes a drainage control seems more likely than direct bedrock control. Thus in some cases drainage definitely influences the direction of pattern lineation. In other cases drainage control seems most likely, possibly including lineations of solifluction lobes.

Troll (1944) and Black and Berg (1963) have reported patterned ground lineations parallel to wind direction. The lineations reported by Black and Berg may be a very exceptional form of lineation - as in the case of the wind orientated lineations recorded at Ytre Garadak during the course of the present study. The lineations of miniature patterns in the Drakensburg reported by Troll to be parallel to wind direction cannot be explained away as 'exceptional'. Thus there is a good case for lineation for at least small forms of patterned ground being determined by wind direction, and possibly some larger forms also.

The most accepted explanation of patterns orientated downslope is in terms of some sort of downslope mass movement, usually described as 'solifluction'. Regardless of whether or not 'true solifluction' is an important mechanism in connection with patterned ground it is certain that frost heave gives rise to some downslope movement. Heaving will be perpendicular to the slope and the material will fall back vertically on thawing. This will result in some downslope movement. Presumably the maximum movement will be in the pattern centres and especially near the surface where there is the greatest heave.

Apart from the wind orientation and solifluction lobe orientations mentioned above all previous accounts of patterned ground have reported patterned ground lineations downslope or across slope in the case of some steps. The observations of the present study suggest that lineations not parallel to the maximum slope may be a relatively common rather than a freak observation, and therefore ideas on how the lineations of stripes and elongates develop need re-examination. The explanation in terms of mass movement alone is not adequate. There is a strong suggestion that drainage direction is important in many cases and that occasionally other factors, especially wind, may influence orientation. These ideas will need to be taken into account when considering hypotheses of pattern origin and development.

7.4.3 Similar Sized Patterns Formed under Varying Local Conditions

The wide variety of markings of patterns in the Seward Peninsula suggests a variety of local conditions. Clearly the level of activity and local microclimate vary. Yet all these patterns are of the same size. This suggests that the overall size is independent of local factors such as microclimate, vegetation type, local soil materials and slope angle. The important implication is that the pattern formational mechanism is relatively insensitive to local variations and therefore any pattern forming hypothesis that is dependant on purely local conditions or needs a very delicate balance of conditions is not satisfactory for more than exceptional cases. This deduction is considerably reinforced by the observation of transitions between relief, stone and vegetation patterns.

7.4.4 Patterns of Different Sizes Superimposed

In the Seward Peninsula on any one site very small patterns (circa 15-20 cms diameter) may be found superimposed upon medium sized patterns (1.5 to 2.5 m) which in turn may be superimposed on large patterns (8 to 9.5 m diameter). The large patterns may be superimposed on ice wedge polygons. Yet in the same area there is no suggestion of a complete range of pattern sizes. The suggestion is that there are controlling factors that form a discontinuous series of patterns. The ice wedge polygons undoubtedly have distinct controlling factors. The other three sizes seem also to be distinct and therefore have different controlling factors. Yet all the three controls can operate on the same site. The implication is that the controls are either very different so as not drastically to interfere with one another, or that they operate at different times.

7.4.5 Patterns preferentially developed in Better Drained Areas

In the Seward Peninsula patterns were developed in the better drained areas and not on very badly drained flat sites. This further suggests some connection between pattern development and drainage. Hopkins and Sigafoos (1951) also noted a strong connection between type of patterned ground and drainage (see especially pp 94 and 95). In Central Alaska extensive areas of large patterns on similar sites to those of the Seward Peninsula were noted during the present study. Medium sized patterns were noted in the same area on steep slopes of eskers and pingos, where drainage was particularly good (see Plate 66). It is important to note that drainage has a marked effect on the depth of active layer and hence drainage effects may be acting to modify the pattern development by modifying the permafrost conditions.

7.5 DEFINITE EVIDENCE OF PATTERN MOVEMENTS

7.5.1 Movement from Margins towards Pattern Centre

The development of a relief pattern which still has relief when all the ice has thawed necessarily implies movement of material. The most common form has a raised centre, suggesting that material moved from the margins to the centre, either at the surface or at depth. Many stone patterns must experience a similar movement or else the margins would be raised. Other explanations are the development of more material at one part of the pattern (e.g. peat developed to give a raised margin), differential erosion of material (Washburn 1956) and vertical sorting due to upfreezing (Corte 1966). The latter possibilities are only explanations of pattern relief in a limited number of cases.

In some sections there is evidence of the route the materials take in moving from the margins to the centres. In the Seward Peninsula there was definite evidence of movement of lobes of peat from the base of the margins downwards and towards the centre (see figure 20). Sometimes the lobes followed the permafrost table inwards and downwards to the middle of the pattern. Hopkins and Sigafoos (1951) report a similar movement of peat fragments rather than lobes. In other cases the lobe appears to start following the permafrost table downwards and then curves upwards before reaching the middle of the pattern.

In East Anglia there was clear evidence of similar movements by sand (see figures 30 and 31). The sandier nature of the sand chalk mixture near the base of the mixed zone suggested that movements of this type had been going on for some time at all pattern sites.

Some evidences for similar movements were seen in Finnmark. Particularly striking was the evidence of movements downwards from the margin and towards the centre in small stripes at Ytre Garadak (see Plate 145 and figure 73).

7.5.2 Dominantly Upward Movement in the Patterns

(a) 7.5.21 Generalised Upward Movements. A number of patterns in the Seward Peninsula and in Finnmark showed generalised upward movements (see figures 7à, 55b, 59 and 70). This was seen in both large and medium sized patterns.

(b) 7.5.22 Localised Movements Upwards. In East Anglian sections the pseudopods (involutions) demonstrated localised upward movement. These originated in the chalk rubble zone or possibly the in situ chalk upheavings, and moved upwards through the sand chalk mixture zones (see figures 27 and 28). In some cases small pseudopods were seen that had moved into the base of the sand trough forms. On slopes pseudopods were angled downslope (see Plate 75).

In the Seward Peninsula no evidence of strictly similar movements was seen. Hopkins and Sigafoos (1951) report similar movements of much less well defined peat forms upwards in the centres of patterns. Perhaps this movement is intermediate between 'generalised' and 'localised' movement. They suggest these movements belong to a second or later phase of pattern development.

(c) 7.5.23 Concentrated movement in the Middle of the Pattern Centres. In one section in East Anglia a layer of large flints across near the base of the pattern was proved to have been moved to form a particularly large pseudopod or dykeform in the centre of a stripe (see section 5.4). This demonstrates movement across the base to the middle of the pattern and movement upwards towards the surface in a discrete fashion. Some medium and larger sized patterns in Finnmark suggested similar movements had occurred with peat, though presumably the peat had originated beneath the margins (see figures 68 and 69).

7.5.3 Movements from the Pattern Centres Outwards

Presumably the accumulations of stones in pattern margins must be taken as evidence of such a movement. It is not possible to say definitely from the present study whether these would move obliquely from the centres to the margins, or whether they would move to the surface and then across the surface to the margins. Many authors have suggested microsolifluction, needle ice and other activity causes surface movement from the centre to the margins. No definite evidence of this was seen, nor was any definitely contradictory evidence seen.

7.6 A REVIEW OF PREVIOUS PROPOSALS OF PATTERNED GROUND ORIGIN FOLLOWING WASHBURN'S CLASSIFICATION

The present writer does not agree entirely with the system of classification of patterned ground origin proposed by Washburn (1950, 1956) and certainly does not accept without qualification many of his conclusions. However, this is by far the most complete review and classification of patterned ground origin and hence it is convenient to use this classification as the framework of a general review of hypotheses in relation to the observations and deductions of the present study. The use of this classification also has the advantage that it is the most familiar framework of classification for English language readers.

In this section each hypothesis will be considered in relation to the initiation of patterned ground and in relation to the continued development once the pattern is established by other processes. The fact that a mechanism has been proposed means that there is almost certainly some evidence in support of it. The present writer is of the opinion that many of the mechanisms reviewed below are important in combination. However, if the original format of the Washburn Classification is to be preserved it will not be possible to consider in this section the various combinations that seem likely. A major weakness of the Washburn Classification is that many subsidiary processes are proposed and criticised as if they were complete hypotheses.

7.6.1 Ejection of Stones from Fines by Multigelation

There is no doubt that in many forms of patterned ground stones are ejected from fines by multigelation and the stones accumulate in the pattern margins. However, some patterns do not have any sorting of stones. Some patterns without sorting of stones seem to be essentially similar to patterns with sorting of stones. Stones may be sorted as a secondary process in relief and vegetation patterns.

The obvious conslusion is that sorting is not a universal hypothesis for the origin of patterned ground. Further it is impossible to envisage the sorting of stones originating most forms of patterned ground. The direction of movement of stones is controlled by the direction of advance of the freezing front and sometimes also by relief. The organisation of a typical regular pattern of even modest size by the ejection of stones in response to a uniform or randomly undulating freezing front is not feasible. The ejection of a stone at one point could be envisaged as producing particularly fast penetration of the freezing front below and around it and therefore causing other stones to be ejected nearer to it. The result would be a stone centred pattern, which is not the usual case. It is also extremely difficult to find any reason why such stone centred patterns should develop at regular intervals simply due to ejection of stones. It seems that the pattern of freezing penetration or relief must develop first, when the regular sorting of stones would follow providing suitable material was present. Only in the case of miniature patterns does the ejection of stones alone seem at all likely to develop a pattern and it is most likely that even in this case other factors control pattern form and size.

Sorting of stones should be regarded as one of a whole series of secondary processes leading to the continued development and perpetuation of patterns once they have been initiated, often perhaps the most important secondary process. Sorting does not seem at all likely to be an initial pattern forming process except in the case of very small patterns and a few unusual patterns.

7.6.2 Mass Heaving

The first type of hypothesis proposed by Washburn under this title is the development of patterned ground due to an uneven layer of frost susceptible material underlying stones (or some other non frost susceptible material). It is unlikely that such a distribution would give a regular pattern. However, in such a case conditions would be very favourable for the marked differentiation of different parts of the pattern if a pattern forming mechanism operated. Involutions are features produced by frost heaving under these conditions when there are no controls of pattern size and regularity (Sharp 1942c).

The second hypothesis of mass heaving according to the Washburn Classification involves the regular buckling of the ground surface. Pattern initiation by this process, followed by other mechanisms perpetuating the pattern formed in this way could explain most of the observations of the present study. It seems unlikely, however, that the necessary forces would develop to buckle regularly extensive areas to produce large forms of patterned ground. It also seems very unlikely that buckling could explain initiation of very small patterns. A comparison with expansion distortion of common materials suggests that equiform and elongate shapes should be present on both horizontal and sloping surfaces. Many other features of the form of patterns in relation to relief also do not seem to conform - especially direction of elongation and regularity of units. A further objection is the absence of observations of similar distortions of frozen surfaces in winter when patterned ground is not established. There are other problems concerning this hypothesis. In the opinion of the present writer this is a possible explanation of the initiation of patterns though it does not seem likely. Further evidence to completely disprove (or confirm) this hypothesis should be relatively easy to collect.

7.6.3 Local Differential Heaving

The observations of the present study and many previous observations indicate that local differential heaving is involved in most, if not all, forms of patterned ground. A wide variety of local differential heaving has already been described in section 7.2. The possible role of local differential heaving in initiating the patterns will be discussed below.

7.6.4 Cryostatic Movement

As noted above buckling of the ground could explain the initiation of many forms of patterned ground but there are a number of problems which make this seem unlikely. Presumably buckling by cryostatic pressure is likely in some of the features reported in the present study. If regular buckling of the ground is not accepted then some other reason for regular distortion of the ground must be proposed. Differential cryostatic pressure develops due to differential advance of a freezing front or differing thickness of the active layer or due to differences of materials. These are not initially caused by the cryostatic pressure and hence cryostatic pressure alone seems unlikely to be able to initiate patterned ground, except by regular buckling, which is a separate process according to Washburn. Once the pattern is established Cryostatic pressure may well be important in effecting movements.

7.6.5 Circulation due to Ice Thrusting

A revised version of the hypothesis put forward by Eakin (1916) would explain all the features of the patterns described in this study. Washburn concludes that this hypothesis can be eliminated in the light of his information. He further states that "significant circulation of material is still unproved" (sic).

7.6.6 Contraction Hypotheses

Contraction due to drying does not seem at all relevant to most of the features described in this study. The only likely relevance is to the very small forms of patterns. The general pattern of contraction cracking does not give stripe and elongate forms (such as in Plate 4). Even in the case of small patterns contraction due to drying may only contribute by guiding the development of a pattern initiated and maintained by other causes (cf. the guiding action of tractor cleat marks described by Hopkins and Sigafoos p 85).

Contraction due to Low Temperatures. The development of heaving due to this mechanism has already been discussed in section 3.33 above and rejected except in the case of ice wedge polygons. Washburn favours initiation of the pattern of patterned ground by contraction cracking due to low temperatures. The present writer does not support this suggestion because the pattern sizes and forms observed do not coincide with the pattern of contraction cracking. In particular the range in the size of individual patterns does not appear to be similar to ice wedge polygons which are undoubted examples of contraction cracking. The development of stripe, elongate and step forms is very difficult to envisage as modifications of a contraction cracking pattern, even if solifluction, rillwork and other processes are also taken into consideration. The suggestion of contraction cracking guiding patterns initiated by other processes also belongs here. Large vegetation patterns in the Seward Peninsula were seen to adapt themselves to fit inside large ice wedge polygon patterns. This hypothesis will be considered again when considering factors controlling pattern initiation (section 7.9.5).

7.6.7 The Rillwork Hypothesis

This hypothesis is not applicable in the case of equiform patterns. Rillwork probably assists in the development of some stripe forms but undoubtedly does not in other cases. In most areas similar types of pattern can be found as equiforms on flat areas or as stripes on slopes. It seems illogical to propose a mechanism which can only explain one manifestation of what appear to be essentially the same type of features.

7.6.8 Solifluction Hypothesis

The importance of solifluction in relation to patterned ground will be discussed below. It is sufficient to note here that the observations of the present study, and particularly the observations of patterns not elongated directly downslope, demonstrate that the origin of stripe and elongate forms cannot as definitely be ascribed to solifluction as suggested by Washburn. Clearly downslope mass movement does affect many patterned ground forms on slopes. Intermediate forms between solifluction lobes and patterned ground have been reported, and were also seen during the present study. However, solifluction, following the classic hypothesis, may well be minimal in most forms of patterned ground.

7.7 SIMPLE VERSUS COMPLEX MECHANISMS IN THE DEVELOPMENT OF PATTERNED GROUND

Washburn (1956) suggested as part of his conclusions that certain mechanisms, as outlined in section 2.5, produced patterns which are end members of a series and that some other patterns are produced by combinations of processes. The reasoning of his major section classifying and evaluating patterned ground origin is based on this assumption (or deduction). He considers each mechanism in turn and makes little or no attempt in the main body of the text to consider how each mechanism might combine with other mechanisms. Washburn evaluates hypotheses by considering whether or not they would form patterns independently. Thus the approach used by Washburn is dependent on this concept of 'end members'.

The primary mechanism or mechanisms producing patterned ground seem beyond doubt to be associated with frost action. A number of hypotheses have been proposed in which freezing is not essential, but with the sole exception of gilgae no other widespread form of patterned ground has been found where there is no association with freezing temperatures. Gilgae are exceptional features distinct from cold climate patterned ground and in fact are usually either not included with patterned ground or included as a special category.

The possible ways in which frost heave can move material have been discussed in section 3.5. These will be considered here in relation to the actual features observed during the present study. It should be remembered that there are a number of subsidiary processes associated with patterned ground that are not primarily the result of frost action. Since these rarely form patterned ground on their own they will not be considered in this section but should be borne in mind.

7.7.1 Explanations of Movements by Simple, Single Mechanisms of Frost Action

Movement by simple freezing dilation followed by thawing. This mechanism essentially only gives a net movement downslope, either the general slope of the area or the micro-slope of an already established pattern. This therefore cannot explain relief patterns on flat ground, and is unlikely to explain all features of many other patterns. It is extremely doubtful if this mechanism acting alone could produce a system of movement that had any resemblance to a circulation.

Movement of material by differential migration of particles at a freezing front. This mechanism is likewise inadequate in that acting alone it could not produce anything resembling a circulatory movement. There is no good reason why peat should move downwards away from the pattern margins and upwards in the pattern centres, if this mechanism were acting alone. This mechanism could explain the origin of some stone patterns.

Movement of differential segregation of ice. Similar arguments apply in the case of differential development of Taber Ice segregations. If materials migrate in a certain direction with respect to the freezing front in one part of the pattern there is no reason why they should migrate differently with respect to the freezing front in another part of the pattern. Though there are various modifications involving different movements with thawing, this mechanism acting in a simple way could not produce a system resembling a circulation. Movements due to differential segregation of ice fed by water by forces external to the ice crystals are likewise not satisfactory when acting alone to explain many of the observations of the present study. Segregation of ice at an upfreezing front could explain many features, but it would be nonsense to suggest that upfreezing is the only form of frost action on the pattern sites described above.

Movement of unfrozen materials by freezing pressures. Any such movements must be from areas of generally higher pressure to areas of generally lower pressure. There are two major objections to this mechanism acting alone to produce many forms of patterned ground. The field evidence demonstrates that the greatest ice segregation is in the pattern centres and therefore it is reasonable to assume that this will be the area of highest pressure. However the evidence in sections shows movements of materials from the pattern margins to beneath the centres which conflicts with the deduced areas of high and low pressure. The second main objection is again that the expected result would not resemble a circulatory system. Further it is unlikely that the freezing action producing the pressure in the unfrozen material would not also act in other ways.

In summary it seems that many of the forms of patterned ground seen during the present study cannot be explained in terms of one simple type of movement, though some stone patterns may be explained by a simple mechanism.

7.7.2 Explanations of Movements by Complex Processes

The idea that a single mechanism of formation of patterned ground is not adequate to explain all occurrences of patterned ground is accepted by many authors. From the above considerations of simple mechanisms of pattern movement by frost action it seems that many of the patterned ground occurrences investigated during the present study must involve a combination of pattern mechanisms.

A separate line of reasoning also leads to the conclusion that a combination of different movements are likely to be responsible for the development of many patterns. There are a number of reasonably distinct types of movement due to frost action, even when the processes of frost action are reduced to their simplest form. There is evidence to suggest that each of the types of movement does occur at least sometimes. Even if some of the evidence has been completely misinterpreted it seems alm almost impossible that only one type of movement due to frost action is responsible for all the features produced by frost action. If frost action does have a number of different ways of producing movements then it is very likely that many sites will involve frost action acting in more than one way. A comparable analogy is wave action. Waves erode by acting in a number of different ways. Rarely, however, would one expect that the features developed at any one site would be produced by waves acting in one way only.

Thus there seems to be good grounds for suggesting that not only is patterned ground produced by a number of mechanisms, but also that many forms of patterned ground can be expected to be produced by frost heaving acting in a number of ways. This differs considerably from the hypothesis of end members advocated by Washburn. The present writer suggests that freezing processes acting in more than one way on a single site is the typical situation. Sites where frost action works in only one way should probably be considered as special cases.

A good example of a study that illustrates the above hypothesis is the mechanism of origin of the patterned ground of the Seward Peninsula proposed by Hopkins and Sigafoos (1951). This mechanism was proposed as a local mechanism and no general claims were made. However, the mechanism was a complex one involving frost action in a number of ways interacting with vegetation (see section 4.3). Although a number of mechanisms or processes were considered to be acting in combination it is not reasonable to consider that any 'end members' are formed by one of the processes acting alone. For some of the processes suggested a 'pure', single process end member is impossible.

7.8 POSSIBLE EXPLANATIONS OF THE DEDUCED MOVEMENTS

Net movements of materials in a vertical plane by frost heave are relatively easily explained, though probably it is often more complex than appears at first sight. Simple vertical movement can be explained by differential segregation of ice (figure 75c), by migration of particles at a freezing front and there are a number of other possibilities. The processes of uplift of stones have been outlined in section 3.56. Non vertical movements are much more difficult to explain, particularly large systematic movements as evidenced in East Anglia, the Seward Peninsula and Finnmark. Sideways movements are evidenced in many different forms of patterned ground. The most likely explanation for sideways movements is that they are caused by non horizontal freezing fronts. Before progressing farther with the mechanisms involved it is necessary to see whether or not non horizontal freezing fronts are likely in patterned ground.

Differentiation of materials is likely to produce an inclined freezing front, either by differences of thermal conductivity or due to differential ice segregation. Greater ice segregation will slow the advance of the freezing front, causing an inclined freezing front when there is variable segregation. An extreme example likely to give a very markedly inclined freezing front is the stone bordered pattern with fine materials in the centre. Deep peat in a pattern margin is likely to have complex effects. The heat penetration in summer would be relatively slow and the heat loss in winter relatively fast (see section 3.2). Over permafrost this would cause a shallower active layer and faster freezing to the permafrost table in comparison to adjacent materials. Presence of deciduous plants differentially concentrated on the margins would have a similar effect since they would be good insulators in summer and poor insulators in winter. Thus plants alone could cause an inclined freezing front. If a pattern has relief then even with uniform materials and uniform rate of frost penetration an inclined freezing front is inevitable. Differential snowcover would also give an inclined freezing front. Thus an inclined freezing front is very likely in patterned ground. Many of the factors concerned would give a deeper freezing front under the margins of patterns than under the centres.

Field observations by Schmertmann and Taylor (1965) demonstrate just such an inclined front developing in sorted patterns developing over permafrost with a horizontal permafrost table (see figure 76). Observations in the Seward Peninsula demonstrated that the active layer was deeper under the pattern centres than under the margins. Observations by Elton (1927) and also Fitzpatrick (1960) in Spitzbergen similarly showed much greater thaw under bare centres than vegetated margins. Washburn (1947) reports very similar results from Victoria Island, Arctic Canada. Huxley and Odell (1924) report relatively fast heat conduction through stony margins.

On the other hand the presence of snow or much moisture differentially on the pattern margin are both likely to discourage deeper penetration of the freezing front into the margins.

Washburn (1956) p 845 criticising hypotheses described as "circulation due to ice thrusting" suggests "The base of the stone borders may not freeze before the base of the central fines ...".

Notwithstanding the objections and exceptions cited above it seems likely that the freezing front is commonly deeper under the margins than the pattern centre. Possibly a horizontal freezing front in vegetation, stone or relief patterns is a rare occurrence.

The simple presence of an inclined freezing front does not alone explain many details of pattern forming mechanisms. In the case of stones and fines in relatively simple patterns the continued development of the pattern if an inclined freezing front is present seems easily understood. Differential migration of particles at a freezing front and movement of stones due to differential Taber ice segregation,* combined with a freezing front inclined towards the pattern centre would naturally lead to concentrations of stones in the margins and the migration of fines to the centre (see figure 77). Such a mechanism has been advocated by many authors (particularly Paterson 1940) and recently refined by Corte (1966).

If a freezing front advanced uniformly into a relief equiform (figure 78a) the freezing front would be inclined. Freezing pressure would

*Footnote. In some cases it is probably not profitable to consider these two processes as distinct.

develop mainly perpendicular to the freezing front, as shown by the arrows in the diagram. In the margin area the pressure acting on the frozen layer will tend to produce compressional stresses in the frozen layer. In the centre the pressure acting on the frozen ground will tend to produce tensional stresses. The tensional strength of rocks and similar materials is only a very small fraction of the compressional strength (Krynine and Judd 1957). It is therefore most likely that relief of pressure upwards will occur in the central area, whereas relief of pressure in the unfrozen material is most likely in the marginal area. This effect will be reinforced by the expansion of residual unfrozen water in the frozen layer (see section 3.32) since this will increase the tensional stress in the central area and further resist compressional stresses in the marginal area. A possible subsidiary factor is that generally speaking frozen fines have lower shear strength than frozen coarse material (Krynine and Judd 1957). Ice content has considerable effect on the shear strength of frozen material and this may also be a factor in some cases. Thus in a relief pattern if there is differential release of pressure (or differential uparching of the surface) this is much more likely under the pattern centres than under the margins.

Figure 78b shows that in a non-relief pattern, where there is a freezing front inclined towards the pattern centre a similar set of conditions is likely to occur. In this case the greater thickness of frozen material under the margins will further encourage movements of the unfrozen, rather than the frozen, material near the margins. If the frozen material of the margin becomes anchored to the permafrost before the complete freezing of materials under the centre (figure 78c) then the chances of upheaving in the margins are virtually zero and movement of the unfrozen material must result with further significant segregation of ice. In all the cases shown in figure 78 it should be remembered that the pattern is three dimensional. This complicates the pattern of stresses but on balance this three dimensional pattern of stresses would seem to favour pressure being relieved by uparching in the centre rather than at the margins.

The resistance to distortion by the margins relative to the centre will markedly affect the movements produced by frost heave. Once a portion of the margin has become 'fixed'* any further marked growth of ice segregations will result in movement of the unfrozen material. This will be a movement with a horizontal component (see figure 79a). Such a movement is unlikely to be reversed when the materials thaw. With a frozen

*<u>Footnote</u>. Although the word 'fixed' is used it is likely that often some <u>vertical</u> movement of the frozen material continues, but that the horizontal component of the heave is relieved in the unfrozen material.

layer that is free to move localised differential ice lensing will tend to result in greater net raising of the material that does not develop ice lenses so readily. If the frozen layer is not free to move then differential development of ice lenses will result in greater net movement of the material developing the most lenses. The resultant postulated movements are shown in figure 79. This explanation seems appropriate for the common observation of patterns with raised centres, both to explain seasonal and temporary relief.

It is necessary to emphasise again the numerous complications that are certain to occur in many cases. For instance once the pattern is well developed increased dilation of the pattern centre is likely since this area usually contains the materials that are most susceptible to Taber ice development. Relief of pressure in the centre will encourage the development of ice lenses in this area whereas higher pressure under the margins will discourage development of ice segregation. Numerous other complex interactions also undoubtedly occur. Detailed consideration of all the factors and forces acting at any one point would be impossible in a document of this nature, even if all necessary data were available. It is interesting to note, however, that many of these complex interactions are cooperative rather than working in opposition.

Applying the above hypothesis to the field observations of this study suggests a number of problems on the one hand and further deductions on the other. Not all the materials will move in from the sides. There is evidence that stones do not move from the margins, or at least that such movement is very limited. The probable explanation is that the stones are first to become fixed to the freezing front. Movement of material away from the margins by heaving pressures moving the unfrozen material would thus not affect the stones. In any case differential migration of particles at a freezing front and differential segregation of Taber ice would not tend to move stones downwards away from the margins. By contrast to the non movement of stones the movement of peat and sand from the margins, as demonstrated in the observations of the present study, suggests that general heaving pressure moving the unfrozen material may be more important than the other two named processes, in this region of the pattern.

The movement of the unfrozen material deserves further attention if the nature of movements in the unfrozen material in general are to be understood. If the soil is considered to be an aqueous suspension then the pattern of movement of the frozen material would be expected to be of the nature of figure 80a, since the proposed material would have effectively a zero angle of shearing resistance. This is essentially similar to the model proposed by Watt et al (1966) following Monteith (1958). The analogy used was a bowl of water freezing from all directions and bursting upwards in the centre of the free ice surface.

This model was suggested as appropriate for the patterns of East Anglia. The direction of flow lines, or alternatively the direction of shear planes, does not fit at all well with the features seen in patterned ground sections.

A search of the literature on soil mechanics suggests a much more satisfactory hypothesis which fits the field evidence admirably. Terzaghi (1943) is responsible for the modern theory concerning failure of shallow foundations. Laboratory experiments of failure under shallow footings show results as illustrated in figure 80b and c (from Little 1961). The pattern of movements indicated would fit extremely well to the pattern of materials seen in patterned ground sections. Where permafrost underlies a pattern section the permafrost table would be the lower limit of failure of the soil and would also provide a preferential shear plane. This would adequately explain why peat lobes (and possibly sand lobes) would follow the permafrost table in many instances. Even if upwards directed pressure was being produced at an upfreezing front, the ice at the upfreezing front would still provide a plane of preferential (easier) shear and hence movements along the lower freezing front would still be likely. Clearly much more quantitative data will be needed before this hypothesis can be rigorously tested. However, even if the appropriate quantitative data were available from patterned ground sites, the complex interaction of forces and distribution of materials would probably prevent this data being tested against existing theory.

A further process aiding movement across the base of a pattern towards the centre could be 'creep' caused by upfreezing from a non-horizontal freezing front (figure 81). Field observations show that the permafrost table under the centre of a pattern is commonly bowl shaped. Perpendicular movements with respect to the upfreezing front would have horizontal components towards the pattern centre. On thawing the material would sink back vertically. This process would also aid the development of the relief of a pattern.

There still remains the problem of why peat or sand should move in discrete lobes. It may be that more frost susceptible material above presses against the lobes during the later stages of freezing, thus helping to preserve the integrity of the peat lobe. The 'guiding' action of the permafrost table is probably important. Another factor, acting when there is downfreezing, is that peat is not susceptible to the development of Taber ice and thus disruption of the lobe by this mechanism is unlikely. Perhaps it is relevant to suggest that a reason for the lobes remaining discrete is simply lack of a mechanism likely to cause their disruption. This cannot be always true, however, since sand is intimately mixed with the chalk in the ridge areas of the East Anglian patterns. Perhaps other factors, particularly time, are important in this case.

Another problem arises with peat and sand lobes where they appear to have moved exactly horizontally across the base of the pattern as at Knettishall, East Anglia and site C2, Seward Peninsula. The best explanation seems to be in terms of the above hypothesis, assuming a horizontal permafrost table. Further criticism and evaluation of this suggestion will need to await further evidence on the actual form of the permafrost table when these lobes moved.

Undoubtedly when considering movements from the pattern centre outwards at the surface the importance of a number of subsidiary processes needs to be considered - especially micro mass movement, eluviation and needle ice action. The evidence of the present study does not suggest any useful additions to the comments of previous workers on these mechanisms. It is perhaps worth noting that where suitable vegetation is present across the whole pattern such movements will be restricted. This may help to explain the particularly steep relief of the medium sized patterns of Finnmark.

The above movements can be summarised in two 'models', a radial movement model (see figure 77) and a circulatory movement model (see figure 82). Careful consideration of the movements involved shows that these two models are not opposed. Many stones take part in a full circulation and the movement of stones may generally be radial (see figure 77) rather than following a circulatory movement. However, the fact that many stones are present in pattern centre areas even in sorted patterns strongly suggests that the sorting processes are either not 100 per cent effective or they are not the only processes moving the stones.

It is almost certain that generally gross movements are greater in the pattern centres than in the margins in many cases. This is offset by the oblique movements near the margins being permanent whereas the movements in the pattern centres are mainly lost when the ground thaws. The exact balance of movements is impossible to predict. Observations of pattern relief suggest that the movements away from the centres are often relatively small, otherwise few patterns would have a marked relief. However, most relief patterns are probably in equilibrium with their conditions of formation so that some sort of balance is implied. For instance the relief patterns of Finnmark are almost certainly in equilibrium with the present climate. Thus outward and inward, upward and downward movements must all be approximately in balance.
A considerable variety of factors will modify the exact movements at a particular site. On many sites a full circulation may not be present. Certainly the field evidence demonstrates that the structures are nothing like exactly reproduced even in adjacent patterns.

It cannot be overemphasised that whilst there is likely to be a circulatory system or part circulatory system due to frost heave in many forms of patterned ground the system will be complex rather than simple.

Several processes will be acting in different parts of the pattern or even at the same place. For example consider the movements at positions A and D in figure 82. At position A movement of unfrozen material by freezing pressure acting from the 'fixed' margin may be the most important process. Some differential segregation of ice and migration of particles at a feezing front may also occur. Upfreezing may further complicate the movement. At D the dominant process is possibly the differential segregation of Taber ice from the downfreezing front (particularly in such sections as shown in figures 25 and 68). However, upfreezing is likely to be most important in the centre of the pattern. Movement of material from the sides under the centre may be the factor giving the greatest net movement. Chambers (1967) has reported observing surface movements like those idealised at C (figure 82). It is again worth noting that many of these movements seem to be cooperative rather than opposing.

In summary the present writer prefers a complex hypothesis involving various frost heave movements giving radial or apparently circulatory net movements, often aided by subsidiary non frost heaving movements at the surface. Simple hypotheses involving frost heave acting in one way only seem to be exceptional rather than general explanations. In many patterns only part of the 'circulation' may be present, or the 'circulation' may be very distorted. Variations are to be expected from site to site and pattern to pattern. Stones and possibly peat do not seem to take part in a full cycle of circulation but it seems likely that materials very susceptible to segregation of Taber ice may well circulate in the true sense of the word. The hypothesis is thought to have general but not universal application.

7.9 THE OVERALL PATTERN OF PATTERNED GROUND

The regularity and form of the overall pattern of patterned ground remains unexplained in most cases, despite the large number of investigations of patterned ground.

7.9.1 A Simple Contraction Model - Ice Wedge Polygons

Lachenbruch (1962), following Leffingwell (1915) has adequately explained the origin of the pattern of ice wedge polygons. The theory suggests that the origin is by contraction cracking of the ground. After frozen ground has been cooled notably below freezing point it will contract. The stresses caused by the contraction may exceed the tensile strength of the frozen material and a crack results. The spacing of the cracks will depend on the strength of the frozen ground, the amount and rate of cooling and the depth of the cracks. The ground will develop successive cracks until the units of ground enclosed by the fractures are not large enough to develop a stress greater than the tensile strength of the ground under the prevailing climatic conditions. The main factor controlling the size of the ice wedge polygons seems to be the amount and rate of cooling. In practice the variations of strength of the frozen ground seem to be less important. Once a crack is initiated and then later ice filled, renewed stress in following years will cause re-fracturing along the same alignments, allowing continued development of the ice wedge. This mechanism is essentially similar to the mechanism of development of drying cracks in mud and cracks in poorly fired pottery. Thus Lachenbruch has refined a theory for the development of one type of patterned ground by contraction cracking. Three points should perhaps be specially noted here.

(i) This is an acceptable theory explaining a regular pattern developed by cold.

(ii) The size of ice wedge polygons tends to be similar in any one area, but there are notable variations of size from site to site.

(iii) Patterns developed by contraction cracking show no elongation on slopes and similar forms occur on level and fairly steeply sloping ground (see Table D6 Appendix D).

7.9.2 A possible Expansion Model

The experiments of Walker (1932) and others, following Bénard (1900 - quoted in Riehl 1954) have demonstrated cellular or polygonal convection patterns in air currents when there was little or no shear across the system. When there is a marked shear elongated convectional cells develop, with the elongation parallel to the direction of shear. True convectional currents are not thought to be responsible for the development of patterned ground, but the pattern of polygonal (equiform) and elongated units does parallel the form of many types of patterned ground. It is possible the variation of form of convection systems noted above also occurs in other types of expansion systems acting with or without a shear. In the case of the convection cells in air the shear is usually wind shear. When the whole expansion mechanism is different, including some material made solid by freezing, the nature of the 'shear' can be expected to be very different.

Earlier writers noted suggestions of a circulation in patterned ground. They also presumably noted the similarities between the convection model and patterned ground forms. Whether or note the analogy is correct it probably explains the persistence of convection theories although the processes involved seemed relatively unlikely.

7.9.3 Indicators of what may control Pattern Form and Size

The use of fossil patterned ground to interpret palaeoclimate depends on being able to interpret the climate at the time of formation of the pattern. Size of a pattern is the most common and easiest determined factor suggested by palaeoclimatic interpretation. Further, knowledge of the controls of pattern size is likely to lead to ideas on how the pattern develops. In view of the importance of pattern size it is remarkable that few authors have discussed the controlling factors.

It is desirable to present evidence and obvious deductions from the present study before entering upon a detailed discussion.

(a) In any one area the pattern size is approximately constant.

(b) Equiforms and stripes are often clearly related on one site. They have notable similarities of form and related size, suggesting that they are formed by the same processes with only a modifying factor controlling elongation.

(c) In some regions there is an optimum size for the region. This is certainly true for the observations of the present study and the work of Troll suggests that this may be true of all patterned ground areas.

(d) Different sizes of patterns superimposed on one site have been reported from many areas.

(e) There is weak evidence to suggest that the pattern sizes are not a continuous series. In particular the largest sizes that can develop without permafrost may be 2 to 3 metres. This is only definitely supported by the present study and possibly some of the observations and conclusions of Troll (1944).

(f) There is evidence that at least some relief, stone and vegetation patterns are formed with the same basic controls.

(g) Large isolate frost scars of the same size as large patterns were seen in the Seward Peninsula. This suggests that in at least one type of pattern the controls on a single unit are the same as on contiguous patterns.

(h) The greatest amount of segregated ice is developed under the centres of patterns.

(i) Large patterns over permafrost commonly have deeper active layers under the centres, though not always (see figure 76 and East Anglian data).

(j) An upfreezing or downfreezing front inclined towards the pattern centre seems to be a common feature. This is probably extremely important in the differentiation of vegetation, stones and relief.

(k) On many patterns the margin is notably smaller than the centre. Usually if the pattern has a notably smaller centre than margin there are signs of degeneracy.

(l) The fact that stripes are not always elongated exactly downslope argues that solifluction or some other mass movement is not the only factor determining elongation of patterns, and may not even be the most important one.

(m) Some elongated patterns have been reported as being elongated parallel to the wind direction. Elongations parallel to wind direction in the very small patterns of African mountains are particularly well documented by Troll (1944).

(n) The elongation of patterns parallel to drainage lines rather than exactly downslope strongly suggests that moisture movement may be important in determining the orientation of patterns.

(o) Patterns in the Seward Peninsula are best developed on slightly better drained sites. This may suggest critical moisture conditions are a controlling factor as well as freezing conditions.

(p) In the case of the large patterns of the Seward Peninsula and East Anglia the size remains generally the same with quite a large variety of local site factors, including notable variations of exposure and hence presumably a variety of microclimates.

(q) On many sites there is a fairly close relationship between depth of pattern formation and size of pattern. This point will be discussed in detail in the following section.

Despite the indications listed above there is no definite evidence of how either pattern size or the overall pattern is determined. Although a number of indications and deductions will be discussed below it is worth noting at this point that a definite solution to the problems of regular (pattern) size and pattern will not be possible till much more quantitative work has been carried out, both in the laboratory and in the field.

7.9.4 Depth of Formation as a Possible Factor Controlling Pattern Size

Despite the complexity of the processes involved in the development of patterned ground on one site and even in one area the size of patterns usually varies within a remarkably small range (see Appendix D).

The depth of formation of the pattern as a controlling factor of pattern size was strongly advocated by Troll (1944). He then went further than this and suggested that depth of formation is controlled by climatic factors, particularly emphasising the contrast between diurnal freeze-thaw cycles and seasonal freeze-thaw cycles. In terms of general pattern sizes and the relationship to climate there is little doubt of the correctness of Troll's interpretation. He clearly demonstrates that very small forms are associated with diurnal freezing cycles. The largest forms are associated with seasonal freezing cycles. However the fact that several pattern sizes occur superimposed demonstrates (as acknowledged by Troll) that the controlling factor of pattern size is not simply depth of frost penetration.

From the present study there seems little doubt that both the patterns of the Seward Peninsula and East Anglia were developed over permafrost. There are small differences in the average sizes of the two areas - those of East Anglia are slightly larger - but these differences seem very small considering the differences of materials and geographic locality. The depth of permafrost at the time of formation of the East Anglian patterns cannot be exactly determined since the sections could be interpreted as evidencing a deepening of the active layer in the later stages. There is little doubt, however, that the depth of the permafrost table was deeper during the formation of the East Anglian patterns than the corresponding permafrost table in the Seward Peninsula. This suggests that there is no exact correspondence between active layer depth and pattern size. The evidence from Northern Scandinavia is less definite, but there is good reason for suggesting that somewhat smaller patterns developed when there was a deeper active layer. The medium sized patterns of Scandinavia show no increase in size northwards, nor in response to local site factors, though there is probably notable variations of depth of penetration of freezing. Again the suggestion is that depth of freezing is not an exact control of pattern size.

On the other hand limited depth does seem able to limit pattern size. Some of the patterns at Ytre Garadak were noted to be especially small, almost certainly because bedrock was present at shallow depth. Some similar observations were made in the Seward Peninsula. Other authors have previously reported similar observations. The lack of large patterns north of the Brooks Range in Alaska is easiest explained in terms of the active layer being too shallow for the development of 9 metre equiforms. The presence of different sized patterns superimposed confirms that depth of frost penetration alone cannot be the control of pattern size. Thus is seems that limited depth of formation can control pattern size but when the depth is not limited then some other factor or factors act to limit the maximum possible size. Other possible factors controlling pattern size are intimately concerned with the controls of pattern initiation and development. These will be discussed very generally in the following section.

7.9.5 Possible Mechanisms of Pattern Initiation

Whilst there are many theories of pattern development there are relatively few theories of pattern initiation, none being fully satisfactory except to explain a handful of sites. It is the pattern of patterned ground that has aroused such curiosity amongst so many workers, yet this remains the aspect that is least well explained. The reason for this is almost certainly the lack of quantitative data. The following is a brief review of possible initiating hypotheses with particular attention to the evidence gathered during the present study.

1. Hypothesis of pattern initiation by a subdivision mechanism modelled on the ice wedge polygon hypothesis (Leffingwell 1915, Lachenbruch 1962). This can be rejected without further discussion for all except ice wedge polygons (and possibly some gilgae) because of the lack of evidence to support such a hypothesis.

2. Origin of patterns by a convection hypothesis (Low 1925). This can also be rejected in the light of present knowledge.

3. Heaving of an uneven layer of materials underlying some different materials. To explain a whole regular pattern the initial 'irregularities' would then need to be in a definite pattern and the hypothesis is therefore applicable only in special cases (Washburn 1956).

4. Heaving of the ground under uniform conditions may naturally give a regular expansion pattern. This might give equiforms on flat areas (Elton 1927) and stripes or elongates on slopes. Perhaps the elongation is due to some kind of 'shear' acting on the heaving units. A very serious objection to this hypothesis is that very many areas show notable expansion of the ground due to freezing without showing any trace of patterning. Comparison with expansion patterns in other materials suggests that regular forms of the type seen on patterned ground sites may well not be typical expansion buckling patterns. It would be fair in this case to say that the lack of evidence revealed in support of this hypothesis is surprising if this mechanism is really applicable. This hypothesis cannot be completely rejected, but certainly needs more evidence in support if it is to gain general credibility.

5. The patterns begin as individual randomly scattered units, more units originating randomly until the whole area is covered (Hopkins and Sigafoos 1951). Presumably the development of units and the initiation of new units would to some extent allow adjustment so as to develop an integrated pattern. The mechanism has the notable advantage that there is field evidence to support it. However, in the experience of the present writer there are relatively few areas of patterns that are in the process of 'becoming integrated' as required by this hypothesis. A further objection is the very great regularity of many striped and aligned elongate patterns. It is difficult to accept that these all initiated as separate centres that have adjusted themselves by competition to become a very regular contiguous pattern. It is difficult to understand how an elongate pattern developing at the foot of a long slope becomes exactly aligned with a whole series of others, starting from random initiation. The well adjusted appearance of patterns with relatively little development is also remarkable. Another objection is that patterns with relatively little development seem to have approximately the same amount of development across a large area, with no signs of some parts of the pattern having initiated first.

In the field there are many irregular patterned areas but the degree of adjustment shown by the more regular parts of pattern areas is not at all suggestive of an origin by random initiation. This mechanism is almost certainly applicable in some cases. It was originally proposed for a particular area but could be much more than a local initiation process. It is almost certainly not a universal hypothesis.

6. The pattern is initiated by some other process that is exploited by the pattern forming processes. The original pattern may be a contraction crack pattern due to low temperatures or to drying or it could be formed by rillwork or some other process. Washburn (1956) strongly advocated the contraction crack pattern as the initiation of the pattern. The main objection to this hypothesis is that contraction cracking does not

explain the development of elongates or stripe forms on slopes. It does not seem logical to propose a mechanism of initiation of equiforms which will not explain stripes and elongates that are essentially the same except for their lineation. There is a lack of reports of a suitable initiation network from many areas. The uniformity of pattern size of some patterns may be greater than normal for contraction patterns. Similar arguments apply in the case of a rillwork pattern initiating linear forms of patterned ground. Undoubtedly where a suitable initiation network already exists pattern forming processes will adapt to this (N.B. Hopkins and Sigafoos 1951 report of miniature patterns adapted to tractor cleat patterns). Thus, whilst some patterns are almost certainly adapted to, or even initiated by contraction crack patterns, this suggestion certainly cannot be accepted as a universal hypothesis for the initiation of the pattern of patterned ground.

7. A unit initiates due to random factors and triggers off other units at the appropriate distance away, thus developing an integrated pattern. The pattern centre is usually characterised by relatively large amounts of heave whereas the margins are generally relatively stable. The development and interactions of centre and margin suggests they are intimately related. It therefore seems likely that the establishment of a stable margin to a single unit would strongly encourage the development of another centre adjacent to the original one. The main objection to this hypothesis is its lack of positive evidence in support. As a hypothesis for the initiation of patterned ground in general it appears neither more nor less unsatisfactory than the best of the previously mentioned hypotheses.

7.9.6 Moisture competition as a possible control of pattern initiation and size

Some more concrete proposal of the mechanism of triggering an adjacent pattern would be desirable. One possibility is moisture competition. An initial unit centre could draw moisture from around it. This would produce a somewhat moisture deficient zone around the original centre and hence reduced ice segregation potential. Thus the freezing front would advance into the margin more quickly and with less heave. The fact that freezing had penetrated more quickly into the margin would mean it was also deeper than the freezing front outside the original unit. This would cause outwards as well as inwards pressure from the margin of the original unit. The outwards pressure would encourage a further centre to develop at the appropriate distance and hence a new unit would be triggered. Moisture competition might also explain a number of the relationships between large and medium sized patterns. Patterns in permafrost areas may develop much of their heave by upfreezing. If upfreezing centres were drawing moisture they would be acting with gravity. If downfreezing centres were drawing moisture they must act against gravity. The fact that an upfreezing front has been demonstrated to develop more ice segregation despite a similar temperature gradient demonstrates that acting with gravity is significant. Perhaps this greater ease of drawing moisture might allow a single centre to develop larger. This could explain why the Seward Peninsula patterns were larger than the non permafrost medium sized patterns of Finnmark, and could also explain how medium sized patterns develop on top of large patterns, since one may be initiated by downfreezing competition and the other by upfreezing competition. The moisture competition hypothesis is only supported by weak indirect evidence. A serious objection is that it makes no provision for the initiation of smaller patterns. If some 'shear' mechanism was acting on the initiating centres then linear patterns would also be explained. The 'shear' need not be a movement but could be some factor either favouring development in one direction or suppressing it in another. This idea would fit particularly well to moisture competition since it would explain patterns lineated parallel to drainage lines, when the favourable moisture supply would encourage elongation. Other advantages of this explanation include its accounting for the relative paucity of 'semi-integrated' pattern areas. It would adequately explain the development of very long stripes and very regular aligned elongates. It would explain good integration at an early stage of development.

A single unit would not be expected normally to initiate a very large pattern area. Presumably several units would begin at scattered centres. The integration of the expanding pattern from each of these centres would explain why some parts of a pattern area are very regular and other parts are rather distorted.

7.9.7. Summary and Comment on the lack of definite conclusions

Probably definite knowledge of the mechanisms of initiation of patterns will await greater knowledge of factors controlling pattern size and pattern development processes. The present writer believes that a triggering mechanism explains more of the field evidence than any other hypothesis extant, with moisture competition as the most likely general control for at least the larger forms of patterns. Depth of formation can be a limiting factor and as such explains some of the regional variations of pattern size. In some cases, however, depth of formation is either very variable or comparatively unlimited yet pattern size remains approximately constant, demonstrating the action of other controls. It is probable that a full answer will only be possible when the patterns can be described in a fully quantitative, rather than qualitative, form. A full quantitative description seems far from possible at present.

This section has been presented as a review of evidence and deductions on pattern size and initiation from the present study rather than with any hope of coming to a definite conclusion. The present study suggests a number of possible new lines of investigation and perhaps eliminates some of the previous suggestions.

7.10.0 SOLIFLUCTION AND PATTERNED GROUND

The present study was not primarily concerned with solifluction. However certain evidence concerning solifluction has come to light. In Finnmark transitional forms between patterned ground and solifluction lobes have been noted by a number of workers. Solifluction is also very relevant to the study of patterned ground in view of Washburn's conclusions that solifluction is the 'key' modifier of patterned ground on slopes.

Washburn states that he is following the original definition of Andersson (1906). "This process, the slow flowing from higher to lower ground of masses of waste saturated with water (this may come from snow-melting or rain), I propose to name solifluction (derived from solum, "soil", and fluere, "to flow")."(Andersson 1906 pp 95-96). Hogbom (1914) and Eakin (1916) suggested that frost heave was important in many occurrences of 'solifluction'. Later writers have gone so far as to include patterned ground as a part of the effects of solifluction (e.g. Hollingworth 1930, Antevs 1949). Many of the features described by Hanson (1950) as solifluction are undoubtedly patterned ground. Lundqvist (1949) describes a whole series of different types of "flow earth" and this includes mainly patterned ground features.

There is no doubt whatsoever that Andersson did not originally intend solifluction to cover purely frost heave phenomena. It is doubtful that Andersson intended to include soil creep with solifluction. As originally described, solifluction seems to be approximately equatable with mud, earth and debris flow, plus a context that suggests some connection with cold climate, though perhaps not strictly. Hence it would be incorrect to include equiform patterned ground with solifluction, since there is no doubt whatsoever that 'slow saturated flow' is not the primary mechanism of origin of these features. Washburn clearly believes slow saturated flow is the main mechanism producing elongation of patterns on slopes. Evidence on this point seen during the present study tends to refute this hypothesis. The elongation of patterns not directly downslope strongly suggests that mass movement is not the most important factor, though possibly a slow saturated flow might follow drainage rather than gravity on the few occasions when these two do not coincide. The observations from Finnmark tend to contradict even this latter suggestion. Elton (1927) and Hopkins and Sigafoos (1951) have pointed out that in permafrost regions the effectiveness of meltwater in producing solifluction is restricted because at the time of abundant water being available the ground has only thawed to a shallow depth. The form of the frost table seen in sections such as figure 6, with a ridge of permafrost beneath the surface ridge front, would clearly tend to prevent solifluction at least until late in the thaw season. Since many arctic regions have very low summer rainfalls the likelihood of solifluction as defined by Andersson is considerably reduced if movement at time of spring thaw is precluded. The distribution of stones seen in some lobe like pattern fronts clearly suggests anything but solifluction (see figure 61). Further if solifluction is responsible for the development of stripe forms of patterned ground from equiforms it seems strange that solifluction lobes usually do not show a very marked elongation downslope even on quite steep slopes. P. Williams (1957), (1961) points out that most solifluction lobes studied by him moved only millimetres or centimetres a year. This may suggest very slow flow but certainly does not seem very much like the speed of movement of the original features described by Andersson - porridge like morasses capable of swallowing camels (Andersson 1906 p 108). In Finnmark, in the Seward Peninsula and in Central Alaska many quite well marked 'solifluction lobes' were seen. Yet the present writer only saw two examples demonstrating true flow and a few dubious examples. This is not to suggest that solifluction, according to its original definition, does not occur, but the suggestion is that other processes may also be working and that solifluction is not perhaps the 'key' factor in producing elongation in patterned ground. The relief stripes of Finnmark are particularly difficult to envisage as the product of solifluction elongating an equiform.

It seems to the present writer that the importance of heave normal to the slope has been severely underestimated by many writers. If expansion is perpendicular to the slope and falling back on thawing is vertical then given only one cycle per annum a 10 cm heave would produce a movement of 17.5 m on a 10 degree slope in 1,000 years, an 8.7 m movement on a 5 degree slope and a 3.5 m movement even on a 2 degree slope. Movements of this order would seem to be much nearer to those expected of the agencies of elongation in patterned ground. 10 cms expansion is a modest expansion for the freezing of a metre or two of 'frost susceptible material'. On many sites the heave would be greater and the differential heave between centre and margin would be of this order. Certainly this would explain the disposition of stones seen in figure 61, would explain how lobe or step forms could develop despite ridges of permafrost beneath lobe fronts, it would explain how movements occur despite the ground being frozen at time of maximum water availability and would also explain the rates and total amounts of movements reported by P. Williams. R. Williams (1968) reports much greater 'solifluction' movements on shallow slopes in chalk areas of Southern U.K. than on steeper non chalk slopes. This could be explainable in terms of the greater frost susceptibility of chalk, where average heaves could reasonably be expected to be greater. There are undoubtedly many factors contributing to the widespread 'head' deposits associated with chalk, (Dines, Hollingworth, Edwards, Buchan and Welch 1940) but frost susceptibility is probably an important contributory factor. This simple 'soil creep' by freezing and thawing does not, however, explain patterns that are not elongated directly downslope.

In summary the present writer deprecates the extension of the term solifluction to cover patterned ground forms clearly beyond the original usage of the word. The present writer does not agree with Washburn that solifluction is the 'key' factor in pattern elongation and in fact doubts whether solifluction is significant on many patterned ground sites. Probably simple creep by frost heaving is much more important than most authors have deduced, though it seems that other factors are also involved in the elongation of patterned ground, as demonstrated very clearly by patterns elongated parallel to wind direction. Finally the present writer is tempted to go farther and suggest that investigation of many 'solifluction lobes' as frost heave phenomena may yield useful results.

8.0 SPECIFIC AREA INTERPRETATIONS

8.1 AREA INTERPRETATIONS OF PATTERN FORMING MECHANISMS

8.1.1 Seward Peninsula, Alaska

It has already been argued in section 4.4 that all the large patterns of the Seward Peninsula are formed by the same processes or group of processes, with modifications due to local variations. The main reasons are the similarities of size and general form, the graduations from one variant to another with no suggestion of clear 'end members' and the variation of pattern sections even on one site where it would be ridiculous to propose different mechanisms for adjacent patterns (see figure 20e and f).

The main differentiations of the patterns are in the vegetation and the materials - silt and peat or stones. The vegetation difference has important effects on the heat budget of the different parts of the pattern and is in turn strongly affected by the heaving effects. The peat is not susceptible to the development of Taber ice, though peat can develop some ice segregations when the supply of moisture is not by the Taber mechanism. In particular peat can develop ice segregations by upfreezing. The special thermal properties of peat have already been described (section 3.2). Certain plants, particularly those commonly found on the pattern margins, act to increase the negative budget of pattern margins because they are good insulators when in full leaf but poor insulators without leaves. The temperatures of the Central Seward Peninsula would almost certainly be favourable for the development of upfreezing. The temperatures of the south coastal area may not allow significant development of upfreezing on most sites.

The present writer envisages the mechanism of development of the patterns of the Seward Peninsula to be very similar to that described in section 7.8 and summarised on figure 82, with the probable addition of upfreezing as an important mechanism of developing heaving pressure. In a well developed pattern the margin would thaw less than the pattern centre during the summer because of differences of thermal conductivity of the ground and differences of insulation. In winter the advance of freezing temperatures into the silt rich material of the centre would be arrested by development of Taber ice whilst moisture was available. The freezing temperatures would penetrate at least as fast or faster into the margins because of the relatively small amounts of ice segregation, the loss of most of the insulating effects of the vegetation and the change of thermal conductivity of peat on freezing. This would give favourable conditions for the marginal area to become 'inflexible' whilst the centre was able to dilate. Differential segregation of ice in the centre giving a convex form in the early stages would help to establish the required mechanical shape for tensional stresses to develop in the centre. The faster advance of the freezing front into the margins would give the required form for compressional strains and hence the margin would become 'inflexible' (figure 78b). When the freezing in the margin reaches the permafrost table this effect would be reinforced (figure 78c). Following the margin becoming 'inflexible' further development of heaving pressure at the freezing front in the margin area would tend to cause movements downwards and towards the pattern centres. Relief of pressure would be upwards in the pattern centre by dilation of the surface of the pattern centre. Additional to this is the extra pressure developed by upfreezing. The inclined upfreezing front would increase the upwards and inwards movement in the pattern centre. The ice segregations developing at the upfreezing front would give a preferential shear plane allowing movement of material across the base of the pattern even though upwards pressure is developing. The lifting up of peat in the pattern centres reported by Hopkins and Sigafoos could be by differential ice segregation or the peat may be simply carried upwards in the general movements of the unfrozen material. Material could be moved from the centre radially outwards by the dilation of the centre as shown in figure 82. Raised relief of the pattern would encourage surface movements from the pattern centre by micro mass movement and other processes. Needle ice could contribute to surface movement outwards. When stones suitable for differentiation are present then a stone marked pattern would develop by the migration of stones to the margin, either by 'circulating' to the margin and then not moving any further or by simple movement perpendicular to the freezing fronts (see figure 77). 'Suitable stones' in this area would appear to be approximately 10 to 15 cms or larger.

If this general mechanism of pattern movements and development is accepted then it seems almost certain that the actual circulatory increments each year are small and the development of large peat lobes across the base of a pattern must be a slow process. Fast or large movements in any one season are very unlikely.

The observations by Hopkins and Sigafoos (1951) of silt injected into the peat lobes appear to contradict this mechanism. However, the variable factor of snowfall must be taken into account. It is likely that in some seasons the patterns would have a good cover of snow trapped in the twigs of the pattern margin whilst the centre would be bare. Under these conditions the freezing front would be deeper under the pattern centre than the well insulated margins. Thus pressure in the unfrozen materials and the inclination of the freezing front would be directed from the centres to the margins and would probably inject silt into the base of the peat margins. No good evidence of this was seen during the present study, though exactly the required snow conditions were seen in Finnmark (see Plate 125). Hopkins and Sigafoos suggest snow conditions in the Imuruk Lake area would favour greater depth of snow over the pattern centres, which would reinforce the main mechanism favoured by the present writer. Snow conditions would undoubtedly vary very greatly from winter to winter.

There are a considerable number of variations of site factors that would give variations of form and section. Most of these are not independent variations and a number are markedly cumulative once certain differentiations have developed. Variations of materials are very important - the relative amounts of silt and peat and the stoniness of the material. The vegetation on the site and its differentiation would cause considerable variations. Vegetation is an obvious example of a factor that can be affected by almost all the other variable factors. Slope has important direct effects on the pattern form, but probably also has important indirect effects, such as freedom of drainage as well as direction of drainage. An effect not immediately obvious is that the stability of permafrost and the depth of active layer are markedly affected by drainage. The development of the pattern undoubtedly will be affected by variations of permafrost depth though it is not possible to say exactly what the detailed effects would be in specific examples. The microclimate of the site would also have important effects, though this in turn would be affected by vegetation, thermal conductivity of the ground and relief. The age of the pattern, stage of development and speed of development on the individual site will have important effects on the structures seen in section and almost certainly also on the vegetation. Possibly climatic or other changes since initiation have affected some patterns.

Some of these variations can be illustrated by suggestions concerning the variations illustrated in figure 20. The variations between 20a, c, d and e could well be due only to variations of the length of time the patterns have been developing. The main variations between 20b and c or g are clearly variations of stone content. Other variations between different sections are clearly due largely to variations of the relative amounts of peat and other materials. There could be a time development series from 20 h or g to e to d. This could be a normal development series, or perhaps g and h are 'stable' sites whereas d and e have developed differently due to a deepening of the active layer following a small climatic or drainage or vegetation or other change. The variations between 20 e and f, which are modelled on adjacent elongates on the same site with identical surface markings, must be clearly due to very local variations. Perhaps in 20 f there has been a lack of any significant development of pressures in the peat of the margin after the margin becomes 'inflexible' in the early winter, because all the peat is frozen before this stage is reached, and hence there has never been any peat starting from the margin towards the centre.

The most problematic feature of the pattern sections from the Seward Peninsula is the stone free or stone poor areas flanking the pattern margins. A number of possible explanations can be advanced but each involves postulated processes for which no other evidence has been detected.

The mechanism proposed by the present writer is much more complex than that proposed by Hopkins and Sigafoos (1951). The mechanism proposed by Hopkins and Sigafoos was designed to explain the same suite of movement evidence, but a relatively limited range of pattern section variations. Many of the factors taken into account during the present study were also evaluated by Hopkins and Sigafoos, and indeed their paper provided inspiration for a number of the conclusions of the present study. The mechanism synthesised by Hopkins and Sigafoos is, however, not acceptable to the present writer (the mechanism is outlined in section 4.3 and idealised in figure 18). Hopkins and Sigafoos suggest there is lateral thrust of the materials of the central area into the peat margins. No special explanation for this is given, nor why there should be a sideways thrust rather than the distortion upwards which is incontravertably evidenced in almost all pattern centres. This sideways thrust causes peat in turn to be moved downwards towards the pattern centres. The lack of uplift of the margins in response to the sideways thrust is "because the rigid layer of frozen peat, reinforced by living stems, is sufficiently strong to resist* upward movement" (p 91). The form of freezing front needed to cause the peat to move downwards towards the pattern centre along the route demonstrated by the evidence (as shown in figure 18) would give forces which would oppose such a movement. The lack of adequate reasons why there should be marked sideways thrust, the doubt concerning the ability of roots to resist what must be considerable heaving pressure and the contradictory pressures that would be developed by freezing fronts as postulated by Hopkins and Sigafoos are the main factors that lead the present writer to reject this mechanism.

The present writer prefers the tentative hypothesis of initiation from scattered centres which each trigger further pattern development around them, so that most of the patterns are initiated in relation to their neighbours. This is based purely on the appearance of the surface pattern. The proposal by Hopkins and Sigafoos that the pattern initiates by continued random initiation of frost scars till the whole site is covered seems inadequate to explain the more regular relationships of some pattern areas (see also section 7.9.5).

8.1.2 East Anglia

The mechanism of origin proposed by Williams (1964) for the patterns of East Anglia appears to be a mass heaving hypothesis. "An attractive explanation is that actual heaving of the till set up the pattern by producing a surface microrelief of troughs and swells. The depressed

Footnote*. The original reads 'resists', presumably due to a typesetting error.

portions of such a pattern would become infilled with blown sand and solifluoted material and form the partitions now seen" (Williams 1964 p 343). The evidence noted during the present study of pure sand being moved into the base of the buried ridge forms and the nature of the sand-chalk mixture demonstrate that at least some of the sand was present when the patterns were formed. Williams suggests that the 'stone lines' seen at Thetford Heath may have accumulated in cracks as described by Drury (1962). The observations at Grimes Graves clearly rule out such a possibility, though there may be more general similarities between the patterns of East Anglia and the vegetation-relief patterns described by Drury. Williams does not attempt any comments on the actual mechanism of heaving beyond that the chalk is very frost susceptible.

Watt et al (1966) suggested that there are similarities between the East Anglian patterns and the patterns described by Hopkins and Sigafoos (1951) and state "An expedition to Alaska to make detailed comparisons between the Breckland patterns and those studied by Hopkins and Sigafoos is now under way." (p 257). The arctic study referred to was in fact the present study, carried out by the present writer, though not referred to by name. The present writer agrees that there is a general similarity with the patterns described by Hopkins and Sigafoos. The details of the mechanism proposed by Watt et al are, however, somewhat difficult to understand. Watt et al correctly deduce the former presence of Taber ice lenses evidenced by the laminations, but seem confused in that they refer to laminations in the "sandy pockets". The simple analogy of the freezing bowl of water is used as the model for the origin of the involutions qualified by "differential moisture contents would provide the necessary basis for forming the bonds between the frost at the surface and the permafrost; drier places between would be the places of least resistance." (Watt et al 1966 p 256). The forces then developed would produce involutions and the surface of the in situ chalk could also be "thrown into waves". The involutions were proposed as being formed previously or contemporaneously with the main patterns. The main patterns are described as non-sorted patterns and therefore belonging to one of two types - either ice wedge polygons or 'spotted tundra' (frost scar) features. The patterns described by Hopkins and Sigafoos (1951) are then quoted as an example of 'spotted tundra' features and the mechanism proposed by Hopkins and Sigafoos is reproduced with some small differences. Watt et al appear confident of the former presence of peat and the former permafrost table is interpreted as being shallow under the troughs and deeper under the centres.

The mechanism of origin of the patterns of East Anglia proposed by the present writer is virtually identical to that proposed for the patterns of the Seward Peninsula and idealised in figure 82. The sand-chalk mixture takes the place of the silt rich mineral soil and the sand (with or without peat) takes the place of the peat. The general features and evidences of movements are essentially similar for both areas, with the exception of the well marked pseudopods.

The pure chalk does not act exactly like the silt in the Seward Peninsula. The evidence of ice skins on chalk fragments and the lack of laminations in the chalk rubble lobes seems at first sight to be contradictory. However, it should be remembered that if the moisture supply to the first formed ice lenses is continuous and balances the rate of conduction away of heat then the freezing front will not advance till the moisture has been exhausted i.e. a large single lens will develop at the contact with the pure chalk rather than a series of ice lenses through the body of the chalk. The implication is that chalk is almost a perfect medium for the supply of moisture by the Taber mechanism, so that multiple lenses do not commonly develop in pure chalk. The chalk in the majority of the pseudopods was so well compacted that it would be as efficient in the passing of moisture as an unbroken chalk fragment.

The horizontal layers of sand across the base of some sections would mean a horizontal permafrost table if the mechanism proposed in this thesis is accepted. The horizontal voidal layer also strongly suggests a horizontal permafrost table. Providing there was a differential advance of the downfreezing front this would not suggest a fundamental difference from the Seward Peninsula patterns and in fact might be identical to some patterns of the Seward Peninsula since no observations of the permafrost table were obtained from stone patterns.

The movements evidenced by most of the pseudopods cut across the lines of movement of the main pattern deduced from other evidence. The pseudopods also suggest a heaving cell of very different size to that of the main pattern (as also noted by Williams 1964). It seems almost certain that the pseudopods are secondary features, probably developed at a late stage when undoubtedly the active layer would have deepened. The size of the units suggested by the pseudopods make it tempting to correlate these with the 'medium' sized scars seen on the larger patterns of the Seward Peninsula and of Finnmark. However, the small pseudopods in the base of the sand filled trough forms show that the pseudopods are not exactly comparable.

The pure chalk pseudopods show clear evidence of having moved upwards through the sand chalk mixture i.e. moving differentially. This movement is very likely due to differential Taber ice development. The exact mechanism would appear to be complex since the evidence of lamination demonstrates that the freezing front lagged behind in the chalk pseudopods, which is exactly the reverse to the advance of freezing fronts in the case of stones being moved upwards differentially by Taber ice. A laboratory study of the differential movement of chalk through sand-chalk mixture could well lead to advances in the knowledge of the processes by which differential Taber ice development effects movements. Without any experimental quantitative data it seems futile to speculate on the details of the mechanism, particularly since the exact mechanism of this movement does not affect the general mechanism of origin of the East Anglian patterns.

8.1.3 Finnmark

8.1.3.1 Medium Sized Patterns. The most widespread patterns, and also the patterns that appeared most in balance with the present climate, were the medium sized relief patterns (1.5 to 2.0 m). These were all very similar in surface form (see Plates 137-139). There were notable variations in section (see figures 68-70 and Plate 140). However all the features seen in section can be fully explained by the unified mechanism described in section 7.8 and summarised in figure 82. The proportions of figure 82 were actually modelled on an 'average' medium relief pattern of Finnmark. Taking figures 68 and 69 as examples, since the peat must originate at the surface there are two possible ways in which the peat moved to its present positions. Either it moved into the pattern from the top of the ridge downwards or it moved inwards from the flanking hollows. Any mechanism of moving material vertically downwards into the centre of the raised area seems unlikely, whereas the explanation shown in figure 82 would explain how this material could move in from the troughs. In a number of cases the peat is not now joined to the peat in the troughs. However the 'curled' lobes are easiest explained as having moved from this direction. The very common 'central dykeform' of peat can be explained by the movement upwards in the centre. Figure 70 and Plate 140 show different forms of section in patterns with a similar surface form. These can also be explained by the unified mechanism of figure 82. Variations of section must be expected if there are variations of the type, form and amounts of the materials in which the patterns initiated, e.g. in figure 70 there is very little peat to form structures such as seen in figures 68 and 69 and therefore it is not surprising that such structures are absent.

The development of very similar structures when the large patterns divide into smaller sized patterns (figure 54) demonstrates that similar development processes are acting in the patterns once they are divided. The very well differentiated structure seen in figure 54b strongly suggests that after dividing the movement of peat was relatively rapid and complete. This is not surprising since the relief of these patterns is particularly well marked and the freezing fronts would be relatively steeply inclined. This would suggest that movements with a horizontal component can be particularly effective in this type of pattern.

8.1.3.2 Large Patterns. The interpretation of the large patterns of Finnmark is somewhat difficult. It is perhaps fair to say that the large patterns of Northern Scandinavia are only active on well 'favoured' sites near the coast and probably also only active on favoured sites on the Finnmarksvidda. Even where they are most active it is doubtful if they are fully active, though probably a few exceptional sites are. The majority are definitely degenerate in appearance and many show signs of breaking into smaller patterns. The conclusion that the large patterns are mainly degenerate or only partly active makes many interpretations difficult. The problems of interpreting the pattern size have already been referred to. The interpretation of the sections is further restricted by the limited number of observations and sections. The problems associated with possible degeneracy are illustrated by the pattern shown in figure 55. This pattern shows signs of being a 7 m elongate that has been divided into two 3.5 m elongates, and may well 'soon' divide again in a similar way to the nearby patterns shown in figure 54a.

As a result of these doubts the present writer does not intend to speculate on detailed mechanisms of formation beyond what has already been put forward in earlier sections. The unified explanation put forward in section 7.8 and summarised in figure 82 could explain most of the features and modified within reason, could explain all of the features seen in the various sections. Certain features of all the large pattern sections strongly suggest different parts of the movements idealised in figure 82.

The large patterns at Ytre Garadak and the section excavated (figure 71) appeared as a notable exception to the above. The presence of only traces of 'frost susceptible' materials suggests these patterns cannot be forming by a similar mechanism to the other patterns of Finnmark. The slopes are too steep and the materials too coarse to allow frost heave in the absence of 'frost susceptible' materials due to the ground being saturated. The single fact that the most stable vegetation forms the 'centres' of these patterns demonstrates that they are markedly different from all other patterns described in this study. The conclusion from all the site evidence is that these patterns are at present maintained by wind and possibly also reindeer action. Whether or not frost action had some part in the original formation of these patterns is impossible to say.

8.1.3.3 <u>Small Patterns</u>. Small patterns were not studied in detail during the present study. The small patterns of Ytre Gardak (see figures 72 and 73 and Plates 144 and 145) do, however, deserve some further comment. The movement of peat downwards and towards the centre of some patterns, and the relief of the patterns, suggests that some, if not all, of the processes idealised in figure 82 may well be active in these patterns.

8.2 PALAEOCLIMATIC DEDUCTIONS FROM PATTERNED GROUND

8.2.1 General Problems

The potential use of the patterned ground of East Anglia as a palaeoclimatic indicator was one of the main stimuli for initiating the present study (West and Donner 1958). However the interpretation of palaeoclimate from fossil patterned ground is far from being an easy task. A number of writers have attempted to relate distribution of active patterns to modern climate. The most notable is Troll (1944) who attempted a world survey and concluded that patterned ground could be primarily divided into diurnal and seasonal forms, and further suggested the seasonal pattern forms could be divided into arctic and subarctic. The differentiation of these different types is mainly based upon their size. The studies of Pewe (1963, 1966) give data for palaeoclimatic interpretations of fossil ice wedge polygons. This study is rather exceptional in patterned ground studies, partly because ice wedge polygons are an exceptional type of patterned ground.

A considerable problem arises when interpreting the current distribution of active patterned ground because of the difficulties of determining the level of activity of individual patterns (see section 4.4). This particularly applies to larger sizes of patterned ground where it is not feasible to attempt to destroy patterns and see if they are reformed (Miller, Common and Galloway 1954). Some guidance can be gained from indications of past climates in an area, but this can very easily lead to 'circular' deductions.

Gradwell (1957) and Tallis and Kershaw (1959) have described small patterns that are only intermittently detectable. The clear implication that they are 'active' sometimes, demonstrates the truth of the statement by Black (1966) that the limits of periglacial regions and phenomena "are fluctuating today just as they have through the Pleistocene and bulk of geologic time" (p 331).

Another problem arises because there are a range of climatic factors that may affect patterned ground. The mean annual temperature has been used by many authors when interpreting patterned ground. Even if this were a true indicator precise interpretations cannot be expected. The mean annual temperature necessary for the development of permafrost can vary from 0--6^{o}C(Muller 1947). However a consideration of the forces and mechanisms of patterned ground formation suggests that mean annual temperature alone is not a very good summary of the pattern forming conditions. The winter conditions are more critical in many cases, i.e. the rate of lowering of temperature, the absolute minima and duration of low temperatures and snow cover. In permafrost areas the depth of active layer and hence the conditions during the thaw season may be most important in determining the pattern form. Williams (1961) and Lundqvist (1963) discuss some of these problems in relation to Scandinavia. Williams suggests that depth of penetration of freezing is important and notes some of the factors influencing this. Lundqvist found a poor correspondence between mean annual temperature and patterned ground which led him to suggest that mean annual temperature is only important on a broad scale and that edaphic conditions are more important in determining local distributions. The factors controlling edaphic conditions are legion.

The frequency of freeze thaw cycles has been commonly interpreted as a probable formative factor. The work of Frazer (1959) in Canada demonstrated that the number of freeze thaw cycles was greater in the milder south of Canada than the North. Clearly freeze thaw is not the primary factor affecting the distribution of many types of patterned ground. Troll (1944) pointed out the importance of freeze thaw cycles in forming diurnal patterned ground and also their relative unimportance in developing larger patterns. A number of different observers have found differing penetration of freeze thaw cycles. Cooke and Raiche (1962) working at Resolute had difficulties in determining the number of 'effective' freeze thaw cycles but report that actual penetration of short period cycles was only 2.5 cm. Taber (1943) reported similar penetrations in Alaska. Jahn (1963) found that short period freeze thaw cycles penetrated 20 or 30 cms in Eastern Europe. The evidence from the latter report suggests that a diurnal-seasonal division of patterned ground forms is oversimplified.

The problems of the effects of seasonal variations from high to low latitudes and from maritime to continental climates was discussed for modern patterned ground by Troll (1944). The palaeoclimatic conditions are very difficult to evaluate. Insolation during glacial winters and summers in the British Isles cannot have been exactly like the high arctic today, leading to the suspicion that other climatic elements may also have varied. Obviously particular care is needed when making 'long distance' interpretations.

Further problems arise in the use of patterned ground as a palaeoclimatic indicator due on the one hand to the characteristic variability of patterned ground and on the other hand to the similarity of structures that can develop under clearly different conditions. The variations of pattern sections in one area and even on one site demonstrate the first point. The similarity between the movements indicated in patterns of very different sizes in different regions illustrates the second assertion. Pattern size seems to be the best indicator of climate since this is the most constant feature in any one region. Variations of form in section and marking (vegetation, stone and relief) seem to be due to local variations. However, the presence of more than one pattern size in an area demonstrates the need for caution in making palaeoclimatic interpretations based upon size. It will be obvious that a small number of fossil patterns can be unreliable as an indicator since they might be formed by some local 'intensifying' factor or they might be patterns of a 'lower' rank' formed under a climate severe enough to produce very different patterns.

8.2.2 Interpretation of the Patterns seen during the present study

In the central Seward Peninsula the large patterns (8-9 m equiforms and 6-7 m stripes) seem to be active and in balance with the present climate, though possibly some sites have been more active in the past. There are indications that in the south of the Seward Peninsula the conditions are submarginal for the formation of large patterns. There is evidence of climatic fluctuations since the last glaciation (Hopkins 1959a and b, Hopkins, Macneil and Leopold 1960, Colinvaux 1964). Since there is evidence of both a warmer and a colder climate the past climatic record is not very useful in interpreting the formative climate. There are similar patterns in Central Alaska. The climate of Candle seems to be approximately similar to that of the Central Seward Peninsula, Nome typifies the south coast and Paxson is slightly lower in altitude and therefore possibly somewhat milder than the nearby areas of large patterns in Central Alaska (see Table X below). Other smaller patterns are present in the Seward Peninsula and Central Alaska - particularly 'medium sized' patterns and miniature patterns.

	Nome (a)	Candle (a)	Paxson (a)	Alta (b)	Kirkenes (b)	Kautokeino (b)	Cambridge (c)
M.A.T.	-3.27	-6.6	-4.9	1.2	0.1	2.6	10.0
MART	25.2	34.5	32.2	21.1	22.1	27.5	24.0
Max MT	9.7	11.6	11.2	13.6	12.1	13.0	13.0
Min MT	-15.5	-22.9	-21.0	-7.5	-10.0	-14.5	3.9
Months Freeze	7	7	7	6	6	7	0
Months Thaw	5	5	5	6	6	5	12
Months Grow	3	3	3	4	4	3	9
^{o}M F	73.5	113.2	93.0	31.8	39.7	71.4	-
^{o}M T	34.0	41.2	34.5	46.7	41.0	39.2	116.0
Ppt	454mm	270.5*	1170 (1961 only)	389	402	310	c600

All temperatures are in ^{o}C, all precipitation measurements in mm.
M.A.T. = Mean Annual Temperature; MART = Mean annual range of temperature.
Max MT (Min MT) = Maximum (Minimum) monthly temperature.
Months Freeze (Thaw, Grow) = Months with freezing (thawing, growing) temperatures.

A monthly temperature of 6.1^{o}C is taken as a growing month. The individual temperatures of all months with mean monthly temperatures below freezing were summed to give degree months of freezing (^{o}M F);

similarly degree months of thawing (°M T) were calculated by summing the corresponding thawing temperatures.

Ppt = precipitation in all forms.

Sources:- (a) U.S. Department of Commerce 1941-48, 1958-65
(b) Vorren 1960
(c) Kendrew 1961
* Hopkins and Sigafoos 1951.

In Scandinavia the patterns that seem in balance with the present climate are the medium sized relief patterns. The larger patterns appear generally unstable and degenerate though occasional sites may be fully active. The mean annual temperatures at Kautokeino suggest that permafrost may well be present on the Finnmarksvidda though the present writer has found no definite evidence. Keranen (1923) reports sporadic permafrost in Finnland and 'Lappland'. Annersten (1966) reports permafrost at Padgelanta detected by temperature measurements. Even on the Finnmarksvidda many of the patterns appear degenerate and in any case not as large as those of the Seward Peninsula, though there were indications that larger patterns had been present. Baranov (1960) gives evidence of much more severe permafrost conditions on the Kola Peninsula 2,500 to 3,000 years ago. Such a climatic change would explain these larger but degenerate patterns.

Having deduced which patterns are active reference can be made to Table X to see the range of (available) climatic indexes that could be taken as affecting the pattern development. Mean annual temperature would only necessarily be important in the case of permafrost and more especially if upfreezing was present. Significant upfreezing probably requires mean annual temperatures of -5°C or possibly lower. All the other factors listed in Table X could have more or less effect. It would appear that the large patterns of the Seward Peninsula probably need mean annual temperatures at least as low as -4° to -5°C with typically the temperature of the coldest month around -20°C. It is difficult to give an upper limit of temperature conditions of the medium sized patterns of Finnmark, but a mean annual temperature of 1° to 3°C might be appropriate. It is interesting to note that similar patterns have been reported in southern New Zealand in a region with a mean annual temperature of about 1°C (Billings and Mark 1961).

The patterns of East Anglia are a somewhat special case of fossil patterned ground in their widespread distribution and excellence of preservation of structures - more detail of the pattern structures can be seen than in almost any reported active patterns. On balance the present writer would say that the similarities of size, structures and movements indicated by the East Anglian patterns suggests they are similar to the patterns of the Seward Peninsula. This must be qualified by saying that the movements indicated were also very similar to the movements indicated in patterns in Finnmark and hence the correlation rests largely on size. Fortunately the voidal layer of the East Anglian patterns strongly suggests the former presence of permafrost. This would most likely mean a mean annual temperature of -1° to -3°C. The presence of a voidal layer may well evidence not only permafrost but also upfreezing. Bearing in mind the evidence of separate ice lenses not developing in pure chalk the upheavings of chalk beds beneath some of the pseudopods are very difficult to explain by downfreezing. Such upheavings are easily explained by upfreezing. Thus upfreezing seems strongly indicated which suggests a mean annual temperature of -5°C or lower. The evidence of ice wedge polygons and widespread involutions in adjoining areas suggested a similar temperature to Williams (1964, 1965). The ice wedge polygons might represent locally more severe conditions rather than a general climate and are much more difficult to date. The evidence from the involutions may not necessarily indicate permafrost, particularly in materials as frost susceptible as chalk. The conclusions from the very widespread large patterned ground seem much more definite evidence to support the earlier deduction. These deductions clearly suggest that the temperatures during the last glaciation were even lower than Shotton (1962) felt confident of proposing.

8.2.3. The Use of Pattern Size as a Climatic Indicator

According to the observations of the present writer, in any one area there is an optimum pattern size. This accords with the work of Troll who particularly demonstrated this for the case of the smaller patterns. The present study has mainly concentrated on the larger patterns.

Many authors quote a wide range of pattern sizes in the area of their investigations. In the few cases where it was possible to check, the presence of a genuine wide range with all intermediate members present was in doubt. Probably many authors have quoted extreme sizes of units rather than averages. Obviously there is a need for a statistically valid number of measurements taken in a consistent way from a wide selection of areas. Until such a compilation is available the following section must be considered to be only very tentative.

Many of the ideas evaluated in section 7.9 concerning pattern size may help in the palaeoclimatic interpretation of pattern sizes. The possibility of pattern sizes being controlled by upfreezing and downfreezing would, if confirmed, mean that large patterns would be very valuable as climatic indicators. Greater knowledge of non climatic controls of patterns size is especially important in helping to evaluate palaeoclimate from very limited numbers of patterns.

The ideas of Troll, coupled with the evidence and literature search of the present study suggest that the following groups of patterned ground can be found.

(a) Very small patterns - 10 to 20 cms size (miniature patterns or zellenboden). These develop with diurnal freeze thaw alone. They are found in tropical and sub tropical mountain regions but can occur even in the high arctic.

(b) Small patterns circa 40 to 60 cms. The exact significance cannot be confidently proposed but they are probably not formed by night frosts alone. They seem to be especially well developed at particularly high elevations in the tropical regions and moderate elevations in temperate regions. They can occur in all colder regions. Possibly they are formed by 'several day' frosts, doubtfully they are formed by especially severe diurnal conditions of freeze thaw.

(c) Medium sized patterns 1.5-2.5 m diameter, formed in climates with a fairly severe winter. Permafrost is not essential in their formation. They are found in all colder climates.

(d) Large patterns of the 'arctic fringes' or 'lower arctic' where the active layer is not too shallow (perhaps at least 75 cm). The 6 to 7 m wide stripes and 8 to 9 m width equiforms are probably typical of mean annual temperatures of -5°C and below.

(e) Somewhat smaller patterns found in extremely severe climates, when the active layer gets so shallow as to restrict pattern size.

This suggested range of conditions of formation of different sizes of patterns is far from proved, nor is it sure whether or not there is a continuous series of pattern sizes between the various groups. Even if the above suggestions are correct there are two notable limitations to the use of pattern size as a climatic indicator. Different types of patterned ground give different sorts of climatic indications. There is a distinct limit to the types of patterned ground that can be expected to give any indication of mean annual temperature, even when pattern sizes have been perfectly evaluated. This limit is almost certainly around the 'medium' size of pattern, which itself may well reflect winter conditions rather than mean annual temperature. Secondly the above series is not a simple small to large series since patterns seem to be smaller in extremely severe conditions as well as in somewhat milder conditions. Notwithstanding all the problems there seem to be definite indications that when adequate consistent statistical data are available patterned ground could certainly give useful supplementary palaeoclimatic data if evaluated with caution.

8.3 THE RATE OF PATTERN DEVELOPMENT

The rate of pattern development is of some interest, especially if the rate is slow, since in this case the well formed patterns in East Anglia may indicate a long period of very cold conditions. There is little direct evidence on this problem. Black (1952) deduced rates of development of ice wedges. Miller, Common and Galloway (1954) demonstrated re-formation of small stone stripes after a few years. This is not feasible for the large patterns because of the probable time involved and because with the destruction of the vegetation and modification of the permafrost the original initiating conditions cannot be confidently simulated. Schmertmam and Taylor (1965) measured the net heave in one season and calculated from the cumulative segregation of ice that the pattern was 150 years old. This method seems to involve several uncertain assumptions.

There is no direct evidence from the present study apart from the fact that some of the patterns of the Seward Peninsula are developed inside Salmon Lake Glaciation end moraines and cannot be more than 10,000 years old. Deduction concerning the movements from the margins downwards and towards the centres of patterns indicates that these movements cannot have been fast. The uplift of the centre of an 'average' pattern during a freezing cycle can be expected to be between 10 and 30 cms. This may suggest movements across the base of the pattern will be in the order of 1 mm to 10 cms per year (freezing cycle). If material makes a 3.5 m 'journey' across the base of a pattern this suggests a time between 35 and 3,500 years - neither extreme figure being very likely. The East Anglian patterns are so well developed as to suggest development over a period of time much greater than 'one journey'. The suggestion is that a large lobe across the base of a pattern may take centuries to develop and that the large patterns of East Anglia might represent thousands of years of cold conditions.

Clearly the present state of knowledge of rate of development of large patterns is unsatisfactory and field observations spanning a representative period of years are highly desirable.

SUMMARY OF THE MAIN CONCLUSIONS

9.1 TOWARDS A MORE RATIONAL UNDERSTANDING OF PATTERNED GROUND

The present writer does not agree with the way that general accounts of patterned ground are presented in standard texts. It is therefore convenient to present the first part of the summary of conclusions in the form of a tentative general account of patterned ground.

Many different writers have put forward differing descriptions of patterned ground, using different terms. There have been even more variants of hypotheses of patterned ground origin. General textbooks seem to regard patterned ground as a feature that is very unusual and little understood. The latter is far from being true, as can be seen by reference to such writers as Troll (1944). Further, regular sized and spaced features are by no means rare natural phenomena if conditions are reasonably uniform. Particular misconceptions seem to have arisen due to authors over emphasising a single type of patterned ground (especially stone marked patterns) and also overemphasising apparent contradictions between the results of different workers.

The term patterned ground is used specifically for approximately regular repetitive features in the regolith that are usually, though not exclusively, associated with frost action. The most important characteristics in describing patterned ground are the surface form, the grouping, the marking, the pattern size and the materials and features of the section. Suggested descriptive terms for these various categories can be seen in Table II, section 2.42 and detailed definitions can be found in the same section. The common types of surface form are equiforms, elongates, stripes and steps. Suggested categories for grouping are isolate and contiguous, with 'grouped' for intermediate cases. The surface marking is by relief, stone or vegetation variations, either singly or in combinations, though infrequently other markings are observed.

Many types of patterned ground are transitional to other types and even to features that are not patterned ground. Equiforms grade to elongates and stripes. All gradations of grouping can sometimes be seen. Gradations of pattern marking can also often be found. Patterned ground grades to solifluction features and other small geomorphic features. Many occurrences of patterned ground are nowhere near perfect geometric patterns and can be quite difficult to detect even when well developed. A view of a number of pattern units and a good perspective angle are needed easily to detect patterned ground. Patterns of small size can be readily detected by a standing man, whereas large sizes are easiest detected from air photographs. The patterns on a single site are by no means all the same size - the standard deviation of pattern unit size is commonly 20% of the average pattern size.

However, the average pattern size on different sites seems to vary less than this over quite large regions. At present these quantitative comments are based on relatively few statistically significant systematic measurements and there is a great need for many more quantitative observations.

Since patterned ground is usually associated with frost action a knowledge of the mechanisms of heaving developed by freezing is essential to an understanding of patterned ground. The expansion when water freezes to become ice produces some heaving pressure. Pressure is also developed by ice segregation, the growing ice segregations being fed by water drawn through capillaries of suitable size ('Taber ice') or the water may be fed by some other mechanism. A further possible mechanism developing heaving pressure is by expansion following contraction due to very low temperatures.

Frost action may cause movement in a number of different ways. Simple freezing dilation causes movements, which are often reversed on thawing. If the dilation is non vertical then a net movement will probably result from a freeze thaw cycle. The sequence of freeze and thaw can also cause net movements because surface dilation is at a minimum when the surface layers are frozen but at a maximum when the surface layers are thawed. Materials may be moved by migration of particles at the freezing front. Differential movements can be caused by differential development of Taber ice, or other ice segregations. Some sorting of stones may be mechanical, caused simply by freezing movements (especially upfreezing) disturbing the unfrozen material. Movements caused by expansion following contractions due to low temperatures are thought only to be important in the development of ice wedge polygons. The movements described above often cause movement of stones towards the direction of heat loss and also the movement of finer particles in the opposite direction. Net movements are particularly likely to result from non vertical heaving. The nature of the movement can be strongly affected by whether the heaving pressure is relieved in the frozen or the unfrozen material. Movements not directly caused by frost action, but noted as affecting patterned ground are eluviation of fines and mass movement both on a large and small scale. The movements resulting from frost action are far from being simple and probably they are often produced by a combination of the above suggestions.

An understanding of the heat flux in frozen ground is also very important. The heat flux in ground subject to freezing temperatures is similar to the normal heat flux in the ground. As in 'normal' ground during the cold season heat continues to be conducted downwards as well as being lost upwards and hence an upfreezing as well as a downfreezing front can develop under suitable conditions. Differences from the normal heat flux in the ground are due to the zero curtain effect associated with the change of state from water to ice and also because ice has a much greater conductivity than water. The rate of penetration of freezing temperatures is controlled by the thermal gradient, the thermal conductivity of the solid particles, the interstitial water or ice and by the migration of moisture to the freezing front, which transports heat to the freezing front. Surface insulating layers are often important, particularly vegetation or snow.

There is an extremely large range of factors affecting the way in which frost action operates and hence in major or minor ways affects the patterned ground. It is convenient to consider the factors affecting patterned ground in a grouping similar to the grouping of soil forming factors commonly attributed to Dokuchayev.

Climate affects patterned ground in a number of ways. Unless suitable climatic conditions are present patterned ground cannot develop. The temperature regime controls the size of patterned ground on a broad scale. When climatic conditions are suitable for development of permafrost this has considerable effect on pattern development. Rates of freezing and thawing are important as well as the absolutely minimum temperatures. Other climatic factors are also important, particularly conditions affecting moisture availability and snow.

The materials in which the patterns are developed also have very considerable effect on the character and distribution of patterned ground. The presence of materials with a suitable capillarity for development of Taber ice strongly affects the nature and amount of frost heave. The thermal conductivity of materials, the presence or absence of stones and shallow bedrock are other important factors. As in Dokuchayev's scheme, some factors can be considered under more than one group heading. The presence of permafrost profoundly affects the behaviour of the ground materials during pattern formation.

Biotic factors have considerable influence on many patterned ground areas. The nature and distribution of the vegetation, itself the result of many complex interacting factors, has very important effects on patterned ground. The insulating effects of vegetation affect frost heave, whilst frost heave modifies the distribution of vegetation. The animal factor is significant in some cases, especially by affecting the vegetation.

Relief and drainage are important factors. Relief (possibly coupled with drainage) controls the surface form of patterns. Equiforms are generally found on flat or gently sloping areas whereas elongates and stripes are found usually aligned downslope or sometimes parallel to drainage lines which are not directly downslope. Steps are only found on slopes. The moisture state of the ground strongly influences both the amount of ice formed, and hence the heave, and also affects the heat flux. Drainage is clearly a major factor affecting the moisture state.

The effects of time on patterned ground have only been evaluated in a few cases. There is little doubt, however, that patterned ground is affected by the duration of the particular conditions of formation. The influence of time is especially obvious in the development of some pattern forms in section, but the time factor must also affect the surface form, grouping and marking in many cases.

The continued development of patterns once they have been initiated is relatively well understood. The development of the initial differentiations is much more difficult. The differentiations may be differences of relief, stones or vegetation or some feature in section. The critical development seems to be some differentiation that leads to a regular pattern of inclined freezing fronts. Once such a pattern of inclined freezing fronts has developed continued development is relatively easily explained. Rather than thinking of 'end member' theories it seems more appropriate to think of models which take into account all the movements likely to affect a single site. There seem to be two models which in reality are closely related. The simpler one is the radial movement model (see figure 77). In this model, once differentiations causing inclined freezing fronts have developed, continued development is by radial movements, either by simple dilation only, or by differential migration of particles at a freezing front, or by differential ice segregation. The simplest example is of stones migrating towards the direction of heat loss and fines away from the direction of heat loss, forming a stone marked pattern (such a pattern would be sorted in the genetic sense). A vegetation pattern could be developed by radial heaving movements without net movements of soil materials, though complete lack of net movements seems unlikely. Doubtfully radial movements could develop a relief pattern.

The more complex model is the circulatory movement one shown in figure 82. There is clear field evidence to support a circulatory movement model. The most plausible explanation involves the form of the frozen materials, the form of the freezing front, and the direction of development of the main heaving pressure so that there are compressional stresses in the margins and tensional stresses develop in the pattern centre. Since frozen ground has a relatively high compressive strength but very low tensional strength the margins are thus relatively fixed, at least for non vertical components of heaving forces whereas the centres are relatively easily deformed by the tensional stresses. This causes heaving pressures to be released in the unfrozen material in the marginal areas and in the frozen material in the pattern centres. As explained in the caption of figure 82 and in detail in section 7.8 a combination of a whole series of movements can act sympathetically to give a general circulatory movement. It is by no means certain whether or not some stones may move radially whilst the rest of the material is taking part in a circulatory movement. Certainly stones do not often take part in a complete circulation but remain in the margins. This seems to be partly because they are often frozen before the margin becomes 'fixed' in the way described above and partly because the tendency of stones to move towards the direction of heat loss tends to offset movements downwards towards the pattern centre. Considering even the simplest heaving a perfect radial movement seems almost impossible and the approximately radial movement model might be considered as a special modification of the more general circulatory model. The many possible modifications of the exact form of the circulatory movement model could account for most forms of patterned ground, excepting notably ice wedge polygons. It should be remembered that few sections are suitable for evidencing more than a small part of the circulatory movement. This is not a universal hypothesis, since ice wedge polygons are definitely very different in their origin. Some patterned ground formed by differential weathering has been reported and there are a number of other explanations for rather exceptional types of patterned ground.

The radial movement model is based on an almost identical model by Paterson (1940), elaborated by Corte (1966). The circulatory model was proposed in a very much simpler form by Eakin (1916) but received little support from later writers. These two models, one of which may be a special modification of the other, unify a whole series of previous hypotheses. Almost all the acceptable sorted hypotheses are united. Mass heaving, cryostatic movements, local differential heaving, eluviation and micro mass movement are all united into the two models. Since frost heaving or frost action can rarely act in one way only a complex model in which various different types of movement are acting in sympathy seems more appropriate than a whole series of 'end member' or single element hypotheses. It seems that patterned ground develops because frost heaving works in a number of ways to produce vegetation, stone and relief variations which further aid development or perpetuation of the pattern. Differentiations that lead to cumulative pattern development are the differentiation of silt mineral soil and peat, differentiation of silt (fines) and stones, differentiation of species of plants or of vegetation and bare ground, differentiation of relief and differentiation of a regular pattern of varying active layer depth.

The initiation of patterns is still not understood. Only some of the factors controlling pattern size are known. Hence it is almost impossible to expect a full explanation of pattern initiation. It seems that depth of freezing and depth to bedrock or permafrost sometimes limit pattern size but do not seem to control its upper limit. A number of lines of indirect evidence suggest that moisture competition may be important in determing pattern size in some cases. The possibility that regular heaving patterns naturally develop in this form is less likely but certainly not disproved. Some patterns may initiate randomly at separate centres and become integrated by interaction, though the regularity of many patterns suggests that this is far from being a universal hypothesis. A more likely hypothesis is that single units initiate and 'trigger' off initiation of neighbouring units at the appropriate distances. Yet another idea is that the whole pattern initiates simultaneously, though the only plausible explanation of this is the regular natural heaving hypothesis. Some authors have suggested that patterns initiate following patterns formed by other processes, particularly rills and contraction cracks formed by either dessication or extreme cold. Neither of these suggestions is satisfactory in most cases, though undoubtedly these pre-existing patterns are very important in some cases. An adequate explanation of how patterned ground initiates will probably not be possible until many more quantitative field and laboratory studies of patterned ground and pattern forming processes have been undertaken.

Patterned ground size is largely controlled by climate, although in most areas it is possible to find also patterns smaller than the optimum for the area. Very small patterns of the order of 10 to 20 cms wide are typical of diurnal freeze thaw conditions and are especially notable as occurring in tropical and sub tropical mountain areas. Small patterns (circa 30 to 60 cms wide) are typically found on tropical very high mountains and mid temperate moderately high mountains. Medium sized patterns (1.5 or so metres wide) seem to be typical of areas with severe winters but no permafrost. Very large patterns (6 to 9 m wide) are typical of the continuous permafrost zone with a moderately deep active layer. Farther polewards the shallowing of the active layer may limit pattern unit size to smaller dimensions. Palaeoclimatic interpretations need to be undertaken with caution due to the possibility of local climate (or microclimate) intensification causing larger patterns than typical for the region and also because smaller patterns may be found under conditions suitable for the development of larger patterns. Obviously the larger the sample of fossil patterns the less doubt there is about palaeoclimatic interpretations.

Finally it should be noted that there have been many studies of patterned ground and more is known about patterned ground than about many other comparable geomorphic features and processes. Certainly there are prospects for a quantitative genetic description of patterned ground long before there is any hope of similarly describing the vast majority of major or minor geologic, geomorphic or soil processes.

9.2 GENERAL CONCLUSIONS

The new scheme of patterned ground descriptive classification proposed in this thesis uses mainly established terms in their accepted usage. The terms circles, polygons and nets are eliminated as primary categories and replaced by a new term 'equiform'. 'Elongate' is introduced as a term for forms intermediate between equiforms and stripes. The use of 'sorted' and 'non sorted' as descriptive categories is rejected. In place of 'sorted' and 'non sorted' the terms proposed for surface marking are relief, stone and vegetation or combinations of these. The usage of the terms is in accordance with earlier usage, but the synthesis is thought to be original. New terms are proposed for pattern grouping, which has not previously been systematically categorised.

Air photographs were used extensively and a common observation was that patterns could be clearly identified when it was not possible to identify the form of the patterns according to the normal descriptive terms equiform, elongate, stripes and steps. Such occurrences were classified as 'meandroid' (see figure 56 and Plate 81). A very experienced interpreter can often assign meandroids to their correct category of form, even when the appearance on the air photograph is very different from the shape of the surface form.

The mechanism of initiation is discussed but no definite conclusions are reached. The present thesis does, however, suggest a complete resynthesis of ideas on patterned ground development, based upon two related complex models - the radial movement model and the circulatory movement model. It might be thought that the radial movement model is most appropriate in producing stone or truly sorted patterns and the circulatory model most easily envisaged as producing relief and vegetation patterns, thus vindicating the sorted and non sorted classes of Washburn (1956). This is,,however, not the case since the circulatory model is equally appropriate for sorted patterns and the radial model might be appropriate for some cases of vegetation or even relief patterns. The present writer believes that most of the accepted ideas on patterned ground origin can be incorporated into these two models, and indeed cooperative movements acting in many different ways are essential to the models. The presence of inclined freezing fronts is also deemed to be essential. The climatic and palaeoclimatic deductions support and amplify the ideas of Troll (1944).

A set of observations thought to be of major importance is the examples of lineations of patterns not directly downslope. There have been some earlier reports of this but it has been previously described only as an unusual characteristic. The deductions from the present study are that drainage may control pattern lineations, which further suggests that moisture may be more important in determining pattern form than had previously been thought. Since drainage is most commonly directly downslope, drainage direction rather than mass movement might be controlling many pattern lineations and hence mass movement may be over-rated in current evaluations of patterned ground origin. Wind can occasionally determine pattern orientation, but there seems little similarity between the exact role of the wind in each of the three examples recorded.

Very few data are available on the rate of patterned ground development. Deductions from the observations of the present study tentatively suggest that rate of development of large patterns is in the order of centuries or possibly millennia, rather than shorter periods.

9.3 IMPORTANT SPECIFIC AREA INTERPRETATIONS

Clearly the area interpretations have formed a major portion of the evidence drawn upon in coming to the general conclusions given above. The details of the pattern forming mechanisms suggested for three main field areas have been set out in section 8.1. The complex interactions involved in specific examples are such that a brief summary is not feasible except to say that the interpretations are in accordance with the general mechanism summarised above, with the exception of the large patterns at Ytre Garadak (see section 8.132).

In East Anglia the very extensive deposits in which the patterns are developed were formerly interpreted as Gipping Till. In the present study these are re-interpreted as being an on site mixture of sand and occasional foreign stones with the underlying local chalk (see section 5.15). Some miscellaneous observations with tentative deductions are reported which may be of importance in the local interpretation of the pleistocene record in other parts of the British Isles (see section 5.13).

In interpreting activity four states can be postulated - initiating conditions, active continued development, mere 'ticking over' and the original development completely inactive, but the patterns still being perpetuated by some other agency. The patterns of the central Seward Peninsula seem to show both active continued development and initiating conditions. In the southern Seward Peninsula initiating conditions do not seem to be present. In Finnmark the large patterns seem to be only 'ticking over' in most cases, but the medium sized patterns are both fully active and seem to be initiating in some cases. In East Anglia the original conditions of development have completely gone, though other factors seem to be aiding the perpetuation of a well marked surface pattern. Evaluation of the climatic conditions for these various states is given in section 8.2. The most important specific palaeoclimatic conclusion is that not only was permafrost present in East Anglia but that the climate indicated was a mean annual temperature of $-5^{\circ}C$ or lower, supporting Williams (1965) conclusion that continuous permafrost was present in East Anglia.

9.4 WEAKNESSES OF THE PRESENT STUDY

As in the majority of studies the main weakness is that more data are desirable. More specific weaknesses are, however, present. The relatively small amount of quantitative data of pattern size is notable. The lack of observations during the winter is also notable.

It is possible that the conclusions have overemphasised relief and vegetation patterns and underemphasised stone patterns. The present writer does not, however, believe that this is true. A more serious deficiency is the very small number of small patterns studied, so that the conclusions may not take these fully into account. It is believed that this is offset by the availability of adequate published accounts of small and very small patterns, particularly stone patterns. The possibility does, however, still remain that some additional model may be more appropriate for small patterns.

The occurrence of all large patterns in materials that are susceptible to the development of Taber ice leads to two suspicions. Firstly that the role of Taber ice may be even more important than is suggested in the present study and secondly that upfreezing may not be of primary importance in pattern formation since frost susceptible materials are not essential to frost heave by upfreezing. Again it is believed these points have been evaluated as well as possible in the present state of knowledge.

Finally, possibly the most important weakness of the present study is the inability of the researcher to read Russian so that there has not been a proper search of this important section of the literature. This is only partially offset by the translations available through such organisations as U.S.A. Cold Regions Research and Engineering Laboratory.

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APPENDIX A

STUDIES IN THE SEWARD PENINSULA, ALASKA

A 1. SITE A5

Location: 64° 33.5' North, 165° 27' West. Map Nome C-1.
Height 30 to 90m (100 to 300 feet).
General Description of Site: The area studied was the south and south west flanks of Banner Peak, a ridge running from north north east to south south west between Snake River and Anvil Creek. The slope had many minor undulations and the slope angle varied from place to place from almost zero to about 8 degrees. The investigation was made very early in the season (30 July) when the frost table was at about 0.5m depth in silty mineral soil beneath a low heath/herb vegetation.

Features Investigated On this site areas of bare soil somewhat raised above the level of surrounding vegetated ground were common. The difference in height was less than 20 to 30 cm and was probably much less later in the season. These bare soil areas were up to 4 or 5m across, sometimes isolated and sometimes in groups. The distribution of scars in a group often made up a crude polygonal or cellular pattern in plan. The individual bare areas making up these patterns were from 3 to 6 metres across, and the 'unit equiform' consisting of bare area with surrounding vegetation was around 5 to 10 metres across*.

Each individual bare area larger than about 1.5 to 2 m diameter was subdivided into a number of smaller units 0.75 to 2 m across. These subdivisions were defined sometimes by a slight dividing depression and sometimes by narrow vegetated areas (see Plate 1). Superimposed on the smaller, 0.75 to 2 m, units were small stone bordered equiforms about 10 to 15 cms across (see Plate 2). The material exposed in the bare areas was a stony silt rich mineral soil. The very small equiforms were defined by lines or bands of small stones surrounding silty mineral soil with few or no stones (see Plate 2). Sections cut through these very small patterns showed that they affected only the top 2 to 5 cms (see Plate 3). Where the general surface had a marked slope small stone elongates, rather than equiforms, were developed (see Plate 4).

* Footnote: Exact figures lost due to theft involving much of the quantitive field data. The true figures are probably nearer to the larger estimates given above.

On steeper sloping parts of the area, up to 6 or 8 degrees, many small individual bare areas about 0.5 to 1 m diameter were seen. These had terrace like downslope margins that were covered by a folded turf layer (see Plate 5), and can be classified as vegetation steps. The term 'turf roll margin' was used in the field to describe this distinctive type of folded turf margin on step-like features. Some turf roll margins were continuous arcs around the downslope margin of the scars, and some were breached as in Plate 5.

On the air photographs of the area which were of a much larger scale than usual many patterns could be distinguished. None of these were correlated with ground observations, probably due to the fact that this was the first investigation of the season. Quite a considerable period of time is needed to become familiar with the pattern manifestations in order to recognise anything but the most perfect sites.

Outline interpretation There is little doubt that these bare soil area features are in fact frost scars.

A 2. SITE X 31

Location: 65° 01.5' North, 164° 43' West. Map Bendeleben A-6. Height 275 m (900 feet).

The site is on the hill known to the inhabitants as Golden Gate Hill, circa 100 m upslope of site X 34 (See Part A 11. for general description and also Plate 28).

The features of interest at this site are large roughly circular to irregular areas with markedly less vegetation than the surrounding ground. Their distribution appeared to be random, sometimes closely spaced, often with varying spacing in different directions from any one circular area. There was no overall network or cellular pattern, though occasionally a few areas together approached a network. Some were more or less overgrown in parts, though their form was still readily distinguished. Many had small areas of completely bare ground. These features were very similar to the 'bare soil' areas seen at Banner Peak though the latter had much more microrelief. Additionally the majority of features on the X 31 site had a comparatively considerable amount of low vegetation on them. Many of the larger features at this site had a well defined turf roll margin up to 30 or 40 cm high along the downslope border. Plate 6 is a well developed example of this type of feature. In some cases a breached turf roll was noted.

The partial or sometimes complete covering of vegetation may suggest declining activity at this site. On the other hand the sharpness of the turf roll features gives a strong impression that these features are still active under the covering of low vegetation. The bare soil areas are good evidence of continuing activity at this site, even if it is at a somewhat reduced level.

Final Classification and Description: Partly vegetated frost scars, not forming an integrated pattern.

A 3. SITES C2, C3, C4, C5

A 3.1 Location: 65° 9' North, 164° 47' West. Map Bendeleben A-6. Height 45 m (150 feet). Aspect: 200°. Slope: 4 to 5°.

Vegetation: On either side of the site which was circa 200 m x 200 m there were willow thickets up to 2 m high (See Plate 7). Downslope of the site the land was gently sloping, poorly drained and carried a dwarf birch/heath/tussock assemblage except near thaw pools. The actual area of the site had two main types of plant association. The first was willow/birch from .3 m to a little over 1 m high, which had dense growth with little or no undergrowth. The second was a low heath association, including various small herbs and grasses. A variant of the latter had patches of small tussocks in the wettest parts of the site. The two types of vegetation were distributed in a roughly stripe form up and down the site, and it was the marked contrast between the two types of community that was the most obvious character of the patterned ground at this site. The stripes were not always continuous, and there were many areas where the vegetation distribution was irregular (see Plates 7 and 8). At ~~many~~ points there were cross bars of willow/birch across the heath/herb/grass areas. These were frequently associated with low ridges and had a crescentic form rather than being straight cross bars. The average width of the stripes was 6.5 m.

A 3.2 C2 Pit Site

The excavation consisted of a cross pit 8½ m long and 1.0 to 1.2 m deep, extending almost the full width of one heath/herb/grass area, across a willow/birch area, and half way across the next heath/herb/grass area. Stripe width at this site is a little less than 7 m. Running downslope from the north end of the pit a trench was dug both to give a longitudinal section of the features and to provide drainage for the main section (see Figures 4 and 5).

The materials in the section can be divided into four types:

1. Peat
2. Peat with marked quantity of mineral soil intermixed.
3. Mottled dark greyish brown mineral soil (Samples C2/2, C2B3).
4. Very dark grey mineral soil (Sample C2/4).

Under the birch/willow there is a 50 cm thick layer of peat, then some mineral soil and more peat with a somewhat irregular distribution (see Figure 5 and Plate 10). Beneath this there is very dark grey mineral soil. Under the heath/herb/grass areas there is a thin peat layer, circa 10 cm, followed by about 70 cm of mottled dark greyish brown mineral soil. Below this is a continuous peat layer about 20 cm thick beneath the south heath/herb/grass area. Beneath the north area there were two more or less continuous peat layers about 10 cm thick, separated by a layer of mineral soil. Beneath these layers there is again very dark grey mineral soil. A few stones of variable size were present in the section, commonly steeply inclined. The longitudinal section was downslope from the north side of the north heath/herb/grass area. It shows that the upper of the two peat layers is continuous at a depth circa lm for at least 6.5 m downslope and strongly suggests that the lower of the two layers is also continuous. Throughout this length of section the two layers are separated by very dark grey mineral soil. At 7.5 m from the cross section face there was a poorly marked 'bar' of birch plants across the heath/herb/grass area, which is reflected in the 50 cm deep layer of peat immediately below the surface.

The two types of mineral soil distinguished above are easily recognised in the field by their colour. The very dark grey material (Munsell colour) appears to have a greenish or blue-greenish tinge. It is thought that the very dark grey mineral soil is unweathered material and the grey brown is material that has been weathered in the active layer. Hopkins and Sigafoos (1951) differ from the present study in their interpretation of the soil colours. The reddish brown soil colour is interpreted as formed in contact with living and dead organic matter and probably partly due to reddish humic acids. They suggest that the blue grey soil has had most of the iron leached from it. The observations of the present writer which are equally as subjective as those of Hopkins and Sigafoos are not easily compatible with this suggestion. The reddish colour is interpreted as soil that has been weathered (ferric oxide) and the 'blue grey' colour (Munsell description is very dark grey) is interpreted as unweathered or reduced under saturated conditions (ferrous oxide). This interpretation is supported by the fact that samples of the 'blue grey' material oxidised to a mottled brown in 6 to 9 months of storage in a temperate climate. Leaching is in any case likely to be very ineffective in Tundra soils (Tedrow et al 1958). The idea that the junction between the very dark grey and the dark grey brown mineral soil represented the top of the permafrost table was strongly supported in this pit by the fact that roots were common throughout the dark grey brown material but absent in the very dark grey material. The boundaries between the different types of mineral soil in this pit were merging. As will be seen from plate 10 the boundaries of the peat with unmixed mineral soil were frequently sharp.

When the mineral soil was excavated in the frozen state it contained numerous small ice lenses, which were best described as ice gneiss. The peat seemed to contain noticeably less ice, which was irregular interstitial ice rather than lenses. When sample C2/4 was taken it was a lump of ice gneiss.

The relationship of the frost table to the vegetation and features of the section seems of critical importance. When the excavation was begun on 21 July 1965 the frost table was about 50 cm below the surface of the heath/herb/grass areas and about 10 - 20 cm below the willow/birch areas. On 4 September a series of bores in adjoining heath/herb/grass gave an average depth to the frost table of about 90 cm. Bores in willow/birch areas gave an average depth to the frost table of about 55 cm. These bores also confirmed that the general distribution of the peat and mineral soil observed in the main pit was also present in the rest of the area.

The structures seen in the pit are open to several interpretations, Undoubtedly there is a relationship between the thick peat and the willow/birch growing on top, and between the shallow peat and the heath/herb/grass area above. The peat layers at 1 m depth below the mineral soil of the heath/herb/grass area are not easily associated with any present feature of the surface vegetational expression of the pattern. The field relationships suggest two interpretations that might account for the origin of this layer. Firstly it may be a buried surface peat layer. The relatively very uniform thickness and continuity of this layer in the longitudinal section supports this view. The second interpretation is that this layer has been moved by frost action laterally to its present position from the thick peat areas under the birch/willow areas. There are two variants of the buried peat interpretation. The mineral soil may have moved onto the peat by a general downslope movement over the top of a former surface, or it may have been moved up from below on top of the peat layer. The absence of any evidence of breaks in the peat layer that appear likely to have been routes for mineral soil to be moved up from below makes this latter interpretation seem unlikely. In addition, the distribution of small fragments of peat in the mineral soil areas does not give any suggestion of such a movement. There are objections to the idea of a buried peat by either mechanism. The first is that if it was a buried peat layer there is a remarkable lack of roots in the mineral soil below. Secondly, if the dark grey brown soil is accepted as weathered in the active layer, and the very dark grey soil is unweathered, a weathered grey brown mineral soil would be expected below the 'buried peat'. Where there is a grey brown soil below the peat layer it is only thin, and is probably related to the present active layer. Thus the balance of evidence points to the peat in the layers at 1 m depth below the heath/herb/grass areas being moved in by frost action (or some other mechanism) rather than being a buried peat layer.

The lobe or sheet of mineral soil projecting into the main peat area on the section (figure 5 and plate 10) may also have been moved into position by frost action or the peat may have been moved in beneath it. The field relationships do not lead to any clear conclusion. Nor was it at all clear whether the mineral soil is being moved into the peat or vice versa on the flank of the thick peat area.

A 3.3 C3 Pit Site

This feature was typical of the ridge features (or 'bars') in the heath/herb/grass portions of this locality (plate 12). The ridge was circa 40 cm high on the downslope side and 10 cm high on the upslope side, so that the ridge had a small but definite crest (see plate 13). On the top and downslope face of the ridge there were willow shrubs pointing downslope as indicated on the section (figure 6b).

The section was hand excavated in several stages. When the section was first opened there was a definite ridge in the frost table beneath the surface ridge. A puddle of water quickly developed behind this ridge and the material upslope of the ridge was even wetter than normal for this region. The distribution of peat is probably the most striking feature of this section (see plate 14 and figure 6b). Upslope of the ridge there was only a thin surface layer of peat, downslope there was a thick surface peat layer. Under the ridge itself there was a large mass of peat extending down about 50 cm. A thin band of peat extended from the bottom of this peat mass along the section at depth about 50 cm on the upslope side of the ridge. After a metre or so this band became intermittent, though still clearly traceable at the end of the excavation, some three metres upslope of the ridge. This band did not look substantial enough to be a buried surface layer. The peat had a pH of about 8.0 to 8.5.

Elsewhere in the section down to about 75 cm there was either dark grey mineral soil (5Y 1/4) or mottled dark greyish brown mineral soil (10 YR 4/2). Below was very dark grey mineral soil (5Y 3/1), in which there were occasional small peat patches. The mottled and the dark grey mineral soil were intermingled. The mottling was most marked upslope of the peat ridge. The very dark grey material was very easily distinguished in the field, and appeared to be greenish grey by contrast to the material above. The contact between the very dark grey mineral soil and the mineral soil above was very sharp, and this line also marked the limit of root penetration.

Downslope of the ridge this contact was also marked by a layer of strong brown material (5 YR 5/8) some 1-2 cm thick (see figure 6b). This material appeared to be the same material as in the brown mottlings of the mineral soil upslope of the ridge. When the frozen material was excavated the mineral soil contained many small ice lenses in the 'ice gneiss' form, and the peat contained irregular interstitial ice, as in the case of the C2 excavation.

A 3.4 Site C5

This site was a ridge similar to that at site C3 but slightly larger. The section was originally opened with explosives which fortuitously stripped back the unfrozen material leaving the surface of the frost table exposed. The edges of the pit were cut square to expose a clean section and the pit was then photographed, recording the exact position of the frost table when the pit was blasted open (see plates 15 and 16). As in the case of the C3 excavation there was a ridge in the permafrost under the surface ridge. This section was then deepened by hand excavation after allowing the ground to thaw. The structures revealed were very similar to those of the C3 section. The peat mass under the ridge was somewhat larger, extending to about 1 m. Again peat extended upslope at depth in a discontinuous band. The frozen material encountered was identical to that removed from the C3 pit. Unfortunately all accurate written records of this pit were lost but the section only differed from that of C3 in the size of the ridge and depth of the underlying peat. Plate 16 shows clearly the peat ridge and mineral soil at shallow depth upslope of the ridge.

A 3.5 Other Ridge Features on the 'C' Site

Plate 11 shews another similar ridge to those excavated at sites C3 and C5, though this site was not excavated. Near the end of the thaw season auger bores demonstrated that the thaw in these ridges had still not reached the base of the peat. About 200 metres upslope of the C2 excavation (beyond the road shewn on plate 7), there were a number of apparently very similar ridges that were somewhat larger and without any accompanying stripes.

A 4. SITE C1

At the foot of the western end of Labaree Hill (Map Bendeleben A-6), the slope grades into a broad very gently sloping area with occasional thaw pools. Over most of this area the vegetation is cottongrass tussocks and occasional dwarf birch and heath plants. There are ice wedges underlying this area. The position of the actual wedges was marked by a slight depression, with fewer cottongrass tussocks and abundant moss. Along the margins of these slight depressions there is rather more dwarf birch. The irregular polygonal areas outlined by the depressions marking the ice wedges are about 30 m across.

An excavation was made in the centre of a depression (see plates 44 and 45). This revealed frozen material at depth only 10 to 15 cms below moss (July 13th). Either side of this the thaw was rather deeper (circa 30 cm). The frozen material in the centre of the depression (i.e. immediately over the ice wedge) was first moss and frozen moss roots, then clear ice, then alternating clear ice, peaty and silty material down to about 1 m. The depressions act as the drainage channels for this area and this succession probably represents the results of freezing a very wet channel the previous winter. Below 1 m there was wedge ice extending downwards to beyond the limit of excavation at about 2 m. The wedge ice contained dirt bands and bands of elongated air bubbles parallel to the sides of the depression marking the ice wedge. Either side of the wedge there was silty mineral soil with a few stones.

An interesting aspect of this site is the appearance of this proven ice wedge pattern on the air photographs. Where best seen the appearance might be described as an irregular net. However over most of the area it can only be described as a number of vague poorly linked irregular part circles (sic) with occasional closed sub circular shapes. This is a good example of patterned ground which would be described as meandroid on the photos since a pattern can be seen but its exact nature cannot be determined.

A 5. LABAREE HILL

The air photographs of Labaree Hill (map Bendeleben A-6) show a large number of linear downslope features. The largest and most obvious ones are swales, which are marked by areas of much darker vegetation. There are also many much smaller linear downslope features that might be vegetation patterns. Plate 17 shows the candelabra like swales. Plate 18 shows the smaller vegetation patterns which cannot be distinguished on plate 17. A ground traverse demonstrated that the smaller features were elongates and stripes approximately 6 m wide.

A 6. S ITE E7

Location: 64° 56.5' North; 164° 50' West. Map Solomon D-6.
Height 160 m (530 feet).

The site is on a gentle footslope of the Kigluaik Mountains facing south into the Kruzgamepa River valley. The Salmon Lake Glaciation terminal moraine ridges are only a short distance upvalley of the site and there may be deposits of the Nome River Glaciation underlying the site.

The patterns on this site are well marked elongate to stripe forms developed on a slope of about 3 degrees. The patterns were about 6.5 m wide and showed a well marked relief of about 20 to 30 cm (see plate 19). The species present on the patterns were Betula nana/glandulosa, Dryas octopetala, Vaccinium uliginosum, Empetrum nigrum, Ledum decumbens, Arctostaphylos spp and grasses i.e. there was a typical assemblage of the plants commonly found in the areas of patterning. In the depressed (or border) areas of the patterns dwarf birch was predominant though all other species mentioned above were present. On the raised (or central) areas of the patterns grass was predominant, though again all the species listed above were present. The vegetation on the raised area was 5 to 10 cm high and on the depreseed area about 25 to 35 cm. It was notable that the two different areas were marked by differences of growth and density of the same species rather than certain species being present only on one part of the pattern. In particular the dwarf birch and heaths shewed a relatively vigorous shrubby growth habit on the depressed area and a low flattened growth habit (adpressed) on the raised areas. The apparent relief of the patterns was reduced markedly because the tops of the vegetation in the depressed areas were at almost the same level as the tops of the vegetation on the raised area.

A more extensive area of similar patterning was examined on a low rise 1 km to the east of site E7 (see plate 20). Although the patterns are only 1 km from where the photograph was taken it is quite difficult to distinguish them, despite the good vantage point. None of the patterns described could be distinguished on the air photographs, which were rather small scale and not top quality.

A 7. SITE D5

Location: 65° 19' North, 164° 42' West. Map Bendeleben B-6. Height 140 m (400 feet). Aspect 130°. Slope about 2° or slightly more. The site is 700 to 800 m west of Coffee Creek Landing Ground, on the north side of Coffee Creek, a tributary of the Kougarok River.

The site was poorly drained. There was no trace of patterning on the air photographs of this area, which were of particularly poor quality. The patterns in this area had a marked microrelief with bare or nearly bare elevated areas and well vegetated depressions separating the elevated areas (see plate 21). It is worth emphasising that the depressions separated the elevated areas rather than vice versa - this is the usual case, but can be seen particularly well on plate 21. The area of patterning was marked by a series of elongate mounds or continuous ridges with corresponding depressions. The continuous ridges, however, generally showed variations of relief relative to the depressions. The elevated parts of the patterns had many small areas of bare silty mineral soil with abundant angular stones. Other parts of the raised areas were moss or lichen covered with a few pioneer herbs (see plates 21, 22 and figure 7b). The depressed areas had a taller and more vigorous growth of dwarf birch, heaths, herbs and grass.

The section was excavated through a short relief elongate by means of explosives over a period of fourteen days so that the material blasted out was largely thawed. Three types of materials were present in the section - schistose rock fragments, fine mineral soil, and organic matter. Figure 7a and plates 23 and 64 show the distribution of these materials in the section. The material all along the base of the section, at 1 metre and below was very stony. Plate 23 possibly gives the impression of the material being less stony than it actually was. Under the raised area this very stony material extended from the base up to the surface. Under the depressed area, with its relatively dense vegetation, there was a mass of peat extending downwards to around 80 cm depth. Near the surface this peat area was not as broad as the depressed area above, but it broadened below. A moderately thick lobe of peat extended from the lower part of the peat mass towards the raised area to the right. This lobe appeared to curve down slightly at first and then upwards following the margin of the very stony material, and ending fairly abruptly about 25-35 cm below the surface. There was a suggestion of a corresponding lobe on the left side of the peat mass, extending towards the raised area beyond the end of the section. This second lobe was nothing like as well developed, and the material involved would be better described as mineral soil heavily coloured with organic matter, rather than as peat. In a corresponding position on the right hand side of the raised area in the section there was another area of mineral soil stained with organic matter, again flanking the very stony material. This was probably from a similar peat mass under the depressed area beyond the end of the section. The colour of the organic material varied from very dark brown (10 YR 2/2) for surface peat below the depressed area, through dark brown (7.5 YR 3/2) for the peat mass at depth circa 45 cms, to dark yellowish brown (10 YR 3/4) for peat in the lobe extending towards the right. The peat stained soil of the other lobes was dark greyish brown (10 YR 3/2).

Mineral soil with very few stones was present down to about 40-50 cm intermediate between the raised and the depressed parts of the pattern. There were three such areas seen in the section viz either side of the peat mass, and to the right of the very stony area. In each case there seems to be a very similar relationship to the materials and forms adjacent. In contrast to the very stony material this stone poor material is very markedly mottled. The silty material was olive brown (2.5Y 4/4) with large olive grey (5Y 4/3) mottlings and smaller reddish brown mottlings.

The depth to the frost table was not measured accurately at any stage during the work, due to stoniness preventing augering, and the method of excavation used. However it was noticeable during the early stages of the blasting that there was frozen ground much nearer to the surface under the depressed area than under the raised area. The amplitude of surface relief of the feature declined markedly during the course of the excavation, probably due to settling following the thaw of ice. Possibly mass movement of the stony material into the pit contributed to the loss of height of the raised area. Below the raised portion of the pattern, amongst the very stony material at depth circa 1 m, there was a horizontal zone in which there was very little fines. There were voids between the stones in which there was only fine gravel. The coarser material had a thin coating of silty material, which could have been due solely to flooding with turbid water during the course of excavation. No trace of voids were found under the depression area, despite very careful examination. These voids are thought to be an important feature. At this point it is worth noting that it is difficult to think in terms of the voids remaining open with silty material above, and easiest to think in terms of the voids being ice filled.

The origin of the angular schistose stones is almost certainly the bedrock beneath the section. The stones were all of identical lithology. It is thought that bedrock was probably present at a shallow depth below the section, with a similar relationship to that seen 1.5 km to the south west, at site F2.

The mineral soil samples from the section were mechanically analysed and the results are recorded in appendix E. Samples D5/4 and D5/5 were both taken from the nearby stone free area of mottled mineral soil and shew nearly identical particle size distribution with 70% in the silt and clay range, with the peak of the distribution at 6ϕ (.016 mm). The graph of the analysis of Sample D5/7 from the stony area reflects the stoniness of the material, though the sample was not large enough to give an accurate sample of the stones. The finer fraction of the sample is not significantly different from the material found in the stone free area.

Any interpretation of this site must account for the above observations and in particular account for the following points:-

1. There seems little doubt that the angular schistone stones come from below.
2. Some factor is causing the raised area to have very much less vegetation than the depressed area, and some parts of these areas are being kept completely bare of vegetation.
3. The zone of open voids at depth below the raised area needs explanation.
4. The patterns have a marked microrelief.
5. There is a juxtaposition of very stony and stone poor silty material.
6. From the form and position of the lobes of organic material it appears most likely that they reached the position seen in the section

by movement of material from a position under the depressions. An alternative suggestion is that these lobes were an old surface that was buried by material being moved on top. The relative distribution of the materials in the section, however, strongly suggests this possibility is unlikely.

A 8. SITE F2

Location: 65° 18' North, 164° 44' West. Map Bendeleben B-6
Height 85 m (260 feet) Aspect 180° Slope $4\frac{1}{2}$ to $5\frac{1}{2}$°.
The site is 250 m west of the junction of Wonder Gulch with Coffee Creek, which is a minor tributary of the Kougarok River. The section is a road cutting running roughly north east from where the road crosses Coffee Creek. The site is circa 2 km from the crest of the ridge.

The patterns can be seen on the enlarged air photograph (Plate 24). On the ground the patterns are well marked over a large area (see Plate 25). The patterns have an average width of circa 6 m and a microrelief of about 30 cm. The most striking character is the great contrast of vegetation development on the different parts of the patterns. The depressed areas are occupied by shrubs and heath of 30 to 50 cm average height. Dwarf birch and willow are the dominant plants with an understory of heaths and grasses. On the raised areas the vegetation is very short, averaging 10 cms high. Over much of the raised areas there is only a thin covering of 'reindeer moss' with frequent patches of true mosses. There are also some heath plants, but they are very stunted compared to those in the depressed areas. On a few raised areas there were completely bare patches. Some stripes about 50 to 100 m long were observed. There were also many elongate patterns, generally aligned to one another up and down the slope, and separated only by narrow depressed areas.

The relation of the stripes to direction of slope on one part of the site was notable in that the direction of elongation of the patterns was observed to be angled downvalley with respect to the direction of maximum slope and was not in the direction of maximum slope as is usually the case. The difference in angle was measured as 9 degrees. This figure should only be considered as indicating the order of size of the difference in angle since it was not possible to determine precisely the direction of maximum slope with the instruments available.

The section was a cut made during road building in the early 1960's. It was 100 m long and 5 m maximum depth, running at a shallow oblique angle across the slope. The original vegetation came right to the edge of the section and shewed the patterning very clearly (see Plate 26.

There was schist bedrock at depth 3 to 4 m in the section, which was markedly fractured but still in situ. Between 1.5 and 2 m from the surface the material was completely disordered. The spaces between the schist stones contained only fine angular gravel with a thin film of silty material. Thus there was a considerable volume of voids. This type of material was found throughout the section below 1.5 m and it frequently extended right up to the surface. A mixture of angular stones and sufficient fines to fill the voids was fairly commonly found in the top 1 m, or occasionally a little below. Silt with relatively few stones was found much less often, and only in the top 0.5 m. Peat and other organic soil was found at the surface and sometimes down to 0.5 m.

The thickness of peat on the raised areas was generally about 5 cm. The peat thicknesses in the depressions shewed variations in depth between 15 and 40 cms.

The best two adjacent pattern sections were carefully cleaned and recorded in detail (see Plates 26 and 27 and figure 8). The left hand elongate section shewn on the photograph will be considered first. The depression area to the left of this pattern was abnormally deep and badly slumped. The centre depressed area in the photograph was underlain by about 15 cm of peat. The left hand pattern had no sign at all of peat lobes. The materials in the top 1 m of this pattern were approximately equal amounts of stones with voids and stones with silt filling the voids. Despite careful cleaning no distinct overall structure could be recognised. There were suggestions of stony involutions marked by larger stones and by the presence or absence of silt filling the voids. These vague involutions were 1 - 2 m across and could not be particularly related to the pattern above, nor could they be directly related to any other feature visible at the surface. Similar poorly marked suggestions of involutions were found elsewhere in the section.

The right hand pattern of plate 26 (which is also shewn on Plate 27) was markedly different. There was a well marked lobe extending in an arc down to just over 50 cm depth and then toward the surface near the centre of the pattern. There was a corresponding lobe, though smaller and less well defined arcing from the right hand depressed area towards the centre of the pattern. (See figure 8) Above these arcs of peat were areas of fines with few stones, which are easily distinguished on the photograph (plate 27). Other patterns along the section shewed varyingly well developed peat lobes extending from the depression areas of patterns, though none were seen as clearly as those described above. Additional areas of stone poor fines were also observed along the length of the section.

This is a very difficult site to describe and interpret as one set of features because of the variety of sizes and forms of features seen in section. This fact in itself is significant. Compare this with the East Anglian section seen in Figure 36. This difficulty may be due to the site being in some way abnormal. Alternatively it could be due to the section being cut at random across the patterns, cutting sections through varying parts along the length of the patterns. A third reason for the variety could be simply that in any one 'population' of patterns there is a certain amount of variation of form. Examination of the surface of the patterns shewed that there is no more variation on this site than on the majority of sites.

On this site the stripes appeared to be made up of a number of elongated raised areas joining, rather than one raised area elongating the full length of the slope. The alternative explanation for the form seen is that the aligned elongates are stripes that are being divided up. The surface form gave no support at all for this latter suggestion.

The deep depression with associated slumping on the left of plate 26 is worth further comment. Ice wedges were seen within a few hundred metres of this site, in deep muck in the valley bottom, exposed in a mining cut (see Plate 46). The extra deep depression referred to above may mark the former site of an ice wedge. Other deep, slumped depressions were observed elsewhere along the section face, at intervals that are compatible with this idea.

The evidence in this section is not sufficiently clear to decide whether the organic lobes in an arc form are buried surface peat or features moved into place from below the depressions.

<u>Variations of Surface Form and Distribution of Patterns in adjacent areas</u>

Less than 1 km west of the F2 site patterns are found with a very different vegetation balance on a similar slope. The vegetation was generally not so high, there was less birch and very little willow. In their place grasses and heath are more prominent in the depression areas, though the raised areas are similar to those seen at the F2 site.

The D5 site, 1.5 km east of the F2 site, has already been described (Part A7). At site D6 2.5 km north east, patterns on a flat spur at the same height were equiforms with a vegetation almost identical to that described by Hopkins and Sigafoos (1951) for their type tussock-birch-heath polygons (see section 4.3).

On the opposite side of the valley to the F2 site elongate patterns were again present, but restricted to a narrow strip near the creek, in contrast to the much larger area on the F2 site.

About 2.5 km downvalley from the F2 site some very well marked patterns were observed very near to the valley bottom. The slope was about 4 degrees and the aspect was 220 degrees. These patterns had raised areas with vegetation very similar to the raised areas of site F2 i.e. reindeer moss dominant. The depressed areas had a notably vigorous growth of dwarf birch and heaths. The former grew to an average height of nearly 1 m and Vaccinium uliginosum commonly grew to a height of 30 cm. Not only was there a very large contrast between the vegetation of the different parts of the pattern, but the boundaries between the different parts were particularly sharp. The patterns were nearly all continuous stripes with very few irregularities. These were the clearest marked patterns observed during the whole field season. It seems that at this site there are conditions that are particularly favourable for dwarf birch and heaths, and also particularly favourable for strongly defined patterns. It seems likely that a south west aspect and sheltered site are the most important factors.

In summary there is a considerable variation of vegetation and micro relief seen on patterns within a few kms of the F2 site. In addition the presence or absence of patterns at any one site is not easily accounted for. The pattern widths show relatively little variation.

A 9. SITE B1

Location: 64° 56' North, 164° 57.5' West. Map Solomon D-6.
Height 170 m (550 feet).
The site is north of the eastern end of Salmon Lake, immediately west of Star Creek. The general slope of the area is gently to the south, toward the lake. The actual site is on the crest of a minor undulation where there is an area about 200 m by 150 m with a slope of less than ½ degree. It is notable that the site lies 4 to 5 km inside the well marked terminal moraines of Salmon Lake age, and must have been covered by ice during the Salmon Lake Glaciation.

There was a well marked equiform patterned area, the same size as other large patterns of the area. The borders of the equiforms were marked by birch, averaging about 30 cm high, accompanied by a typical assemblage of heath plants. The centres had reindeer moss and very low herbs, generally less than 5 cm high, and frequent areas of bare soil.

An excavation was made across a well marked equiform from the centre to the border. Under the equiform centre grey brown mineral soil was found with only a very thin layer of peat (less than 5 cm.). Under the border there was very much more peat. Patches of red brown stained silt were found in association with the peat under the border. The investigation of this site was carried out early in the season, on July 8th. The depth of thaw at time of excavation was 60 cm under the centre and only 30 cm under the border.

A 10. SITE X4

Location: 65° 02' North, 164° 42.5' West. Map Bendeleben A-6.
Height 162 m (514 feet). The site is on a minor ridge running east south east to west north west on the north flank of Golden Gate Hill

(see plate 28). On the crest of this minor ridge there is an area some 600 m by 200 m that has very well marked patterns. The patterns are dominantly equiforms which were easily seen on the original photos. The top of the ridge is almost horizontal but there is a very slight slope down to the north over much of the site. The ridge slopes away very gently to the south at 2 to 3 degrees and more steeply in all other directions. When the site was investigated there was a prolonged wet spell and water was at the surface in many slightly depressed areas.

Both the relief and the vegetation of the patterns at this site are variable. Almost the whole area is covered with equiforms which form a continuous network across the site, passing into elongate and stripe forms where the slope steepens to the west. For ease of description and reference certain patterns studied have been given 'type' numbers. Gradations between the 'types' are as common as the 'types' themselves and often there is a mixture of different 'types' in close proximity.

Type I. In the middle of the site, on a slope circa 0.5^{o} an equiform with a slightly domed central area was recorded (Plate 29). This site was investigated in early September, which is late in the thaw season. The vegetation of the central areas was dominantly mosses and lichens with low herbs and frequent patches of bare soil. In places stones were being raised by frost action (see Plate 37). The margins of the equiforms were marked by a birch/heath vegetation about 30 to 40 cms high. Birch was very markedly dominant and willow fairly common. The relief and width of the birch/heath borders was quite variable (see figure 9). Some borders had a sharply defined ridge 1 to 1.5 m wide and up to 0.5 m high. Others were broader, up to 4.5 m wide, with the same type of birch/heath vegetation but with little or no relief. Frequently the border of any one equiform varied around its perimeter e.g. compare the left and right hand sides of the equiform shewn in Plate 29. Equiform diameters varied from 7 to 11 m or slightly larger. However the biggest were rather irregular and appeared to be shewing a strong tendency to break up into two or more smaller equiforms. The most favourable size for equiforms is about 8 - 9 m on this site. Very frequently the central area was divided into a number of smaller areas marked by small variations in the relations of the vegetation and the bare ground (see figure 10).

Type II. Mingled with patterns of Type I were patterns with the central area of the equiform showing a much more stable vegetation and rather more relief (see Plate 30). The species represented in this more stable vegetation were the same ones as in the centre of a Type I equiform. The difference was that they formed a much more continuous mat of low vegetation, up to 10 cm high. Around the fairly stable vegetation of the raised central area there was a depressed area with less continuous vegetation and frequent bare patches. Outside this was a border area of birch-heath of the types described above. The raised central mound and surrounding area of less stable vegetation was clearly a closely related variant of the corresponding area of the Type I equiforms. Plate 31 shews a form intermediate between Type I and Type II. Figure 12C shews the measured cross profile of this pattern.

Type III. Towards the south of the site no slope at all was detectable. Cottongrass tussocks became a very noticeable part of the vegetation assemblage, almost certainly a reflection of the even poorer drainage. The patterns here (Type III) were marked by a circular depression about 2.5 to 4 m across with relatively sparse, low vegetation surrounding a central raised area (see Plate 32). Outside the circular depression the vegetation was birch, heath and cottongrass tussocks, with no marked relief. On the mound inside the depression birch was rare and the tussocks appeared to be growing much more vigorously. Willow is sporadically present in all areas, though commoner outside the depressions. The gradation of patterns across the site leaves no doubt that this is part of the same network of patterns. In this variant of the pattern expression the central area is somewhat reduced in diameter compared to Types I and II and the border area is correspondingly expanded.

Type IV. (Plate 33) Nearby equiforms had little or no relief and were marked only by roughly circular areas of tussocks 2.5 to 3.5 m across in an area of general birch-heath vegetation. These resemble very closely the 'tussock groups' described by Hopkins and Sigafoos (1951 pp 84-87). The spacing of these circular tussock groups is similar to the spacing of more obvious patterns elsewhere on the site; these patterns grade across the network into patterns of the other types described above.

Type IVA. Not far from where the Type IV patterns were best developed it was difficult to distinguish any patterning at all. With the eye of faith similarly spaced areas with rather more tussocks than elsewhere could be distinguished. Plate 34 shews where a tracked vehicle had recently crossed the area. Alternating pools and peat areas can be seen in the tracks. In the pools the silty mineral soil could be seen at only 5-10 cm below the original surface whereas between the pools the peat was at least 35 cm deep. This was interpreted as being the subsurface representation of equiforms. The pool areas with silt at shallow depth could be associated with the poorly defined tussock areas mentioned above. This track thus revealed that even when the patterns were very difficult to distinguish at the surface there was a subsurface peat and mineral soil differentiation. It is also relevant to note that no concentrations of large stones were observed along the line of the tracks.

Type V. Towards the western limit of the site another variant of the patterning was seen, which is thought to be of particular importance to the study of the patterns. This variant of the patterns had centres like those of Type I, but borders marked by cobbles with no fines. At this part of the site the ground began to slope away, and the area of this type of patterning was on a slope of 1 to 2½ degrees. The equiforms passed to elongate forms and stripe forms on the steeper parts. Plates 35 and 36 shew pattern borders where birch borders were passing into stone borders. Figures 12a and b shew variants of cross profile of the stone bordered patterns. These profiles shew that on the surface at least an area of fines free from large stones flanked the stone border areas. Where clear stripes were present (slope 2½ degrees) they had an average width of 5.6 m. In the intermediate areas, as seen in Plates 35 and 36 stone borders alternated with borders marked by birch. When excavated it was seen that the birch grew on a shallow layer of peat overlying stones. Intensive probing shewed this relationship continued for a distance where there were no surface signs of stone borders.

Pattern Forms in Section. A section was blasted across a typical Type I equiform at the clearest marked part of its perimeter. The pit was sited so as to show the sectional form across the centre and the border of the pattern. On one side of the pit the section of the border was seen to be a peat ridge, though with no peat extending down below the base of the ridge (see figure 11a). In the opposite face of the pit peat was seen extending deep into the section (see figure 11b). Only very thin surface peat was seen under the central area of the equiform. A small concentration of large stones was noted under the peat ridge in the main face and a better marked concentration at a similar position in the opposite face. However, the quantity of stones involved was not sufficient to suggest that the pattern was an overgrown stone pattern. Other differentiation in the section was not at all obvious. Careful examination revealed that flanking the peat ridge there were areas that were distinctly deficient in large stones compared to the rest of the section. Comparison of the matrix of the mineral soil from the areas with and without large stones revealed no noticeable differences and the boundary between the two areas was indistinct. Some small areas of voids were detected as indicated on the section drawing.

Analysis of samples shewed that the material at this site was very badly sorted. A sample from the 'stone deficient' area was not significantly different from a sample taken from an area where large stones were present.

Two sections cut through nearby birch-heath ridges bordering equiforms revealed similar structure to those described above, i.e. peat overlying minor concentrations of large stones.

The Transitions of the Patterned Area. To the north of the site the Type IV patterns passed gradually into a tussock-birch-heath area in which no patterning was distinguishable. To the west the stone bordered patterns passed into an area of very stunted vegetation with very stony mineral soil where there was no clear indications of patterning. Cut into this area was a pit for road material with a face some 6 to 8 m high. The material was coarse fluvioglacial deposits with only a modest amount of fines. In the upper 60 cm of the face the bedding of the fluvioglacial material was destroyed, presumably by frost action. To the south the patterns passed downslope into an area of willow thicket with no patterning. Downslope of the willow thicket, about 30 m lower than the ridge top, there were excellently marked elongates, width 2 to 3 m, with borders of lichen encrusted stones. All the rock particles were angular schist in contrast to the main site. Frequently the long axes of schist particles were parallel to the direction of slope. These patterns were markedly different from those seen on the west of the ridge. To the east of the ridge top the patterns passed laterally from an area of Type I and Type II patterns to an area where there were raised areas of low vegetation about the same size as the patterns but without birch heath borders. At this point the slope was 2 to 3 degrees. These raised areas passed downslope into mounds of variable size with occasional frost scars, and then into an area of smaller stone bordered equiforms. Farther downslope the stone bordered equiforms passed onto a slightly steeper sloping area of largely bare schistose rock with occasional small frost scars with silty centres.

Summary and Brief Interpretation

The patterns at this site shew a wide variety of surface form and vegetation. A series of pattern 'types' are described. These 'types' are simply examples from a continuous variation of pattern form. The commonest relief form of the patterns is a raised centre and raised margin, though other forms are present. The division of the central area into a number of smaller areas, suggesting a number of heaving centres in many equiforms is thought to be an important character. This feature was well marked on the Type I and on some Type II equiforms.

Using Washburn's classification (1956) the stone bordered patterns would be defined as sorted patterns. From their surface form all other patterns on the main area of the site would be classified as non sorted. Concentrations of stones were proved under borders where none were present at the surface. In general the quantity of stones present decreased eastwards across the site, and the quantity of stones concentrated under the borders also seemed to decline eastwards. In the centre of the site a section shewed that there was a concentration of of cobbles under a thick layer of peat, though not sufficient to support the idea that the pattern was an overgrown stone pattern. The even gradation of all types of pattern and their similar sizes is good evidence of the form produced by similar processes. In particular any theory proposed for the large vegetation ('non sorted') patterns must also be compatible for producing stone ('sorted') patterns.

All the stones on the main area of the site were rounded and sub rounded and a variety of lithologies were present. This material is best explained as being of glacial origin, particulary in view of the good section of fluvio glacial gravels seen just west of the site. This glacial material lies not far outside the limits of the ice of the Salmon Lake Glaciation as mapped by Hopkins (1963), but well inside the limits of the ice of the Nome River Glaciation. There are no fresh glacial or fluvio glacial forms in the area of the site. There are no deposits on the north and east shoulders of the ridge. The top of the ridge is a favourable site for a patch of glacial material to survive. These observations are all consistent with the suggestion that this glacial deposit is a product of the Nome River Glaciation.

A 11. SITE X34

Location: 65° 01.5' North, 164° 43' West. Map Bendeleben A-6.
Height 275 m (900 feet).

The site is on the north and north west facing sector of the north summit of Golden Gate Hill (975 feet). Patterning can only be distinguished with difficulty on the copy of an air photograph seen in plate 28 but was easily distinguished on the original air photographs. The site is very exposed so that generally the vegetation is less than 15 cm high. The forms seen on the air photographs are easily recognised on the ground about 200 to 250 m north north east of the summit. Plate 38 shews the patterns well. The pattern is marked by areas of low heath-birch vegetation and constrasting areas where bare soil and stones are prominent. On close examination the area with much bare soil is divided up into many individual frost scars 0.5 to 2.0 m across. Nowhere is there bare soil across the whole width of the 'bare soil' area, the size of the individual scars being much less than the width of the bare soil area (see figure 13). There are no frost scars at all in the heath-birch areas. The appearance of the scars suggested that they were active individual areas and almost certainly not remnants of larger old scars that had become divided. The vegetation between individual scars was the same as in the area without scars, suggesting soil differences were minimal. This was confirmed by shallow excavation.

A 12. MINIATURE PATTERNS

Sites X32 and X33

Location: 65° 1.5 mins North, 164° 43 mins West. Map Bendeleben A-6. Height 275 m (900 feet).

At this site very well developed miniature stripes were seen. The patterns were midway between sites X31 and X34. The patterns occur on local very short sections of much steeper slope than average. On site X32 the patterns were 15-18 cm width and varied from 13 to 20 cms width, slope 8 degrees (see Plate 39). On site X33 the slope varied from 6 to 20 degrees (see Plate 40). A series of measurements gave the following widths; in cm: 11.5, 12.5, 13, 13, 14, 14, 15, 16, 17, 18, 19, 20, 20. Thus the average width is 15.7 cm and the range from 11.5 to 20 cm. Figure 14 shews a cross section across typical stripes.

A 13. SITE E2

Location: 65° 00.5' North 164° 42' West. Map Bendeleben A-6. Height 260 m (850 feet).

The site is on a west facing slope of a ridge lying between the Kigluaik Mountains to the west and the Kruzgamepa River Valley to the east. The site is only a few kilometres south of Sites X4 and X3 and is on the same ridge. The ridge was probably covered by ice during the Nome River Glaciation (see Part A10).

The form of the patterns at this site was continuous stripes about 6 metres wide with negligible relief at the time of investigation (mid August). The patterns were first recognised from air photographs and were easily recognised on the ground. The pattern was marked by alternate strips with continuous vegetation and strips of bare soil (see Plate 41). The bare soil areas were continuous and not broken into a series of frost scars. The vegetation was dominated by grass though the absence of any tussock habit was notable. Some heath and herb species were present but were relatively few in number. Shallow excavation indicated no subsurface differentiation of the soil. In particular there appeared to be almost no peat developed beneath the areas of continuous vegetation. The whole of the patterned area was underlain by silty mineral soil with a moderate number of stones but without peat. The silty mineral soil is at least 50 cm deep in places, with no indication of a change in material with depth. On the air photographs the patterns of this area passed laterally into the 'scar trains' of site X34, described above, the patterning in the different parts of the area being indistinguishable.

Certain important points emerged from the brief study of this site. Firstly the patterns appear to exist only as a vegetational difference, without any microrelief or soil differentiation. This strongly suggests that in the development of patterning vegetational differences can precede soil differences. Secondly, it is important to note that since there appear to be no soil or relief differences there would be only the vegetational inertia to perpetuate the patterning if the factors that produced the patterning ceased to operate. Judging from the rate of colonisation of artificially cleared areas on similar soils it seems very unlikely that these patterns would survive more than a few decades if the pattern forming processes were not active.

A 14. SITE E3

Location 65° Zero' North, 164° 42.5' West. Map Bendeleben A-6.
Height 250 m (820 feet).

The site is not far from the summit of a fairly flat col about 1 km south west of site E2. Plate 42 gives a good impression of the general area of the site. The finer fraction of the underlying mineral soil is notably silt rich. The coarser fraction of the soil includes boulders with long axes greater than 0.5 m.

The features investigated were large stone equiforms (see Plates 42 and 43). Where best developed the patterns had well marked borders of large stones (cobbles and boulders) ranging in size from long axes of 10 cm up to long axes of nearly 1 m with no fine mineral soil. The largest particles were in the centres of the borders and there was a noticeable trend for smaller particles (long axes 10 to 20 cm) to be concentrated on either side of the coarser material. Material with long axes less than 5 cm did not seem to have been affected by the main sorting processes. The central areas had a silt rich mineral soil with abundant particles up to 5 cm. These fine soil areas had no relief when investigated (mid August). The centres had occasional bare soil patches as seen in plate 43. The vegetation covering the rest of the fine soil areas was dominantly low grass and some herbs. The equiforms ranged in size from 5 to 7 metres in diameter.

The area covered by these patterns was very limited and they faded in all directions. No other patterns were found in direct association with these large stone patterns, but there was a variety of pattern forms within one kilometre or so of the site (see parts A 10, A 11, A 12, A 13).

The central (or fine soil) areas of these large stone patterns very closely resembled the centres of some of the large vegetation (relief) patterns of the Seward Peninsula. The large stone patterns investigated on this site were the best example of this type of patterning seen in the Seward Peninsula. The actual network only occupied a very small area. There appeared to be much more very coarse material present in the patterns than in the mineral soil of the adjacent area. Thus the limited distribution of these patterns may be due to the locally abundant cobble and boulder material.

Though the central areas were flat when the site was investigated they may well have been raised in winter and spring. The bare soil areas indicate at least some activity. It can be seen from plate 43 that the large boulders at the margins of the patterns have a thick layer of lichen. Some of the smaller stones however are relatively lichen free, also suggesting at least some activity of the patterns in recent times (see right hand side of equiform in plate 43).

A 15. SITE E4

Location: An outcrop of marble bedrock forms a small rise some 300 m south west of Site E3. On the steepest slopes to the south of this rise there are small areas of scree deposits derived from the marble bedrock. On other flanks of the rise there are shallow silt rich deposits overlying bedrock. In many places these shallow deposits contain varying sized fragments of marble bedrock.

To the north east of the rise there are small areas of medium sized stone equiforms about 1.5 to 2.5 metres diameter. The slope angle is locally less than 2 or 3 degrees where these patterns are present. The patterns were marked by borders of coarse particles between 5 and 25 cm long, surrounding areas of fine material. The pattern form at this site was markedly different from the rather similar sized stone patterns seen at site A6 described below. The pattern form at the latter site was marked by equiform centres that were isolated discoid patches of vegetation and fines on a ground mass of stones. The pattern form at the E4 site was marked by sorted borders in a general ground mass of fines. Figure 16a and b shows this contrast in idealised form.

A 16. SITE D2

Location: 65° 16' North, 164° 47.5' West. Map Bendeleben B-6. Height 180 metres (600 feet).

The site is at the head of Little Ptarmigan Creek, a very small south flowing tributary of the Kuzitrin River, rising on the west flank of Coffee Dome. The slope of the site varied from 2 degrees near the watershed to 10 degrees some 200 to 250 metres downslope. The underlying material is a stony silt rich mineral soil, with varying amounts of peat closely related to the vegetation.

A series of bare soil areas were investigated through various slope angles. On the shallowest slope (circa 2 degrees) a number of bare soil areas were seen which appeared at first sight to be randomly distributed. Close inspection revealed that in a few places a poor cellular network was present. Occasional features were present in this area that resembled the peat ring/tussock ring features described by Hopkins and Sigafoos (1951). These were almost certainly old, overgrown frost scar forms.

Downslope bare soil areas making up a poorly integrated pattern passed into well developed elongate patterns. These were marked by centres of bare soil or areas of similar form more or less covered by reindeer moss. The 'centres' corresponded to the bare soil area farther upslope. The borders were marked by birch/heath vegetation.

Farther downslope the elongates continued on a slope angle of 10 degrees. The centres had rather more vegetation, and were frequently divided into many units downslope. At the downslope margin of the central areas there was often a peaty ridge which was part overturned (see figure 15). There is little doubt that the bare soil areas are frost scars. This site appears to show a sequence from non integrated bare soil areas to poorly integrated equiforms to well integrated elongate patterns. The part overturned peat ridge on the downslope margins of some elongates closely resembles the 'turf roll margins' described from site A5.

A 17. SITE FM1

Dome Creek Ice Wedge Site

Location: 65° 18.5' North, 164° 43.5' West. Map Bendeleben B-6. Height 75 metres (250 feet).

The site is a section in a hydraulic mining cut running up the course of Dome Creek from the junction of Dome Creek with Coffee Creek. Gold mining still in progress in 1965 had exposed the section described below, which was some 200 to 300 m upstream from the junction with Coffee Creek.

The hydraulic mining exposed a section some 4 metres high in frozen muck (see plate 46). Near the base of the section there was a large, almost flat topped ice wedge. The flat top was some 3 to 3.5 m down from the ground surface. Above this large wedge a small ice wedge was present with a roughly flat top some 30 to 40 cm from the surface and extending down to 1.2 or 1.3 m. The whole section below a depth of a few tens of centimetres was frozen. The frozen muck overlies old stream gravel, now being worked for gold. This gravel presumably represents the ancient stream bed of the valley. There was virtually no evidence discernible on the ground surface around the site to indicate that there was wedge ice below. The section was investigated in company with Dr. D.M. Hopkins and the outline of the following interpretation was suggested by him and agreement of interpretation was made on site.

In brief the section is easiest explained in terms of three climatic phases.

1. A period of intense cold when the lower, large ice wedge developed. The size of the wedge suggests that the wedge was developing for a long period of time, and thus suggesting that this climatic phase was prolonged.

2. A period of milder climate during which the wedge thawed down to its present level.

3. A following cold period when the smaller, upper ice wedge developed.

A slight variation on stage 2 above would be the burial of the large wedge by accumulation of peat over the top of it after a prolonged period of growth. This could either be more or less in situ peat or colluvial peat. This would likewise suggest a period of milder conditions. Certainly the limited downward extent of the upper ice wedge obviates the possibility that peat accumulated steadily over the large old ice wedge without climatic change.

Another possible explanation of the features of the section not involving climatic change might be local rapid accumulation of muck on the top of the large ice wedge followed by another wedge developing in this material. However the valley has a regular gentle profile and there is virtually no possibility of sudden accumulation by mass movement. Judging from the present stream action in the general area it seems very unlikely that large quantities of colluvial peat could be mobilised without amelioration of climate.

Since the upper small wedge comes within 40 cm of the surface this represents the maximum depth of thaw in this material for a period of some years. Observations in the general area suggest that 40 to 60 cms is about the average depth of thaw in this type of material. The direct implication of the shallow ice wedge appears to be that for at least half a century (?) and most likely at least several centuries (?) the thaw seasons have not been significantly warmer than present.

A 18. SITE A6

Location: The site is on a horizontal bench some 50 m wide and 2 - 300m long facing south west near Snake River within the general area described in part A1. The bench was covered with angular rock fragments between 5 and 25 cms long. All fragments were of the same lithology and most of those on the surface were thickly encrusted with lichens.

The features investigated were medium sized stone patterns (about 1.5 m diameter). These were excellently marked on this one limited area (see plate 47). The patterns were marked by roughly circular vegetated areas between 0.5 and 1.0 metres in diameter, surrounded by areas of rock fragments of the type described above. Shallow excavation into the vegetated patches shewed that there was very little fine soil present. The vegetated areas were patches of living and dead organic material with a little fine soil perched on a stony groundmass. The excavation was not deep enough to prove that there was no fine material amongst the stones, but there was certainly not enough to fill the interstices of the stones beneath the vegetated area excavated. Figure 16a shews the type of section form indicated by excavation.

A 19. GENERAL DISCUSSION OF ICE WEDGES IN THE AREA

The air photographs suggest that ice wedge patterns may be present in a high percentage of the area studied. It should be remembered that it is impossible by use of air photographs to distinguish between the majority of active and fossil ice wedge polygons (Hopkins, Karlstrom et al 1955). Air photographs of the Kuzitrin Flats area show abundant ice wedges.

On the ground there were frequent depressions or differently vegetated linear features up to a few metres broad possibly marking ice wedges. Again these observations would not distinguish between active, inactive and fossil ice wedge polygons. A considerable effort was needed to prove ice wedges were present at a particular site (see part A4). Very little ground ice was seen in natural sections, which were generally degraded by thawing. Plate 48 shows a typical result of thaw and slumping at the edge of a thaw lake (Hopkins 1949, Hussey and Michelson 1966).

Conversation with miners and other persons in the area confirmed that ground ice and probably wedge ice is common. Large masses of ground ice were described by the local inhabitants as 'glacier ice', which was reported common in river banks and other sections. The average size of ice wedge polygons in the area was around 30 m or smaller. Many of those on the Kuzitrin Flats appeared to be smaller than this - possibly as little as 15 m in some cases.

A 20. INVOLUTIONS

A good section shewing weakly developed involutions was seen in the bank of the Kuzitrin River circa 100 m upstream from the road bridge. (See plates 50 and 51) The section consisted of contrastingly coloured layers of dominantly coarse sand and gravel. The involutions were developed in or immediately adjacent to a layer containing rather more fines than the rest of the section. It is interesting to note that a very similar section had already been observed by the writer in a section in the United Kingdom, near Durham.

In a gravel pit near to Golden Gate Creek a linear area of apparently upheaved fines was investigated. A small pit revealed an involution like form developed in silty material with distinctive colourations (see plate 52). There was a very clear suggestion that the linear feature had developed along a track of a heavy vehicle, which in turn suggested that the involution had developed since the pit came into use and possibly since the pit was last used. The road was opened only a few years before.

Apart from these isolated observations no other involutions were seen in the area. This was probably due to the general scarcity of sections and the absence of suitable materials rather than implying that the climate was not suitable for involution development.

Generally two contrasting materials seem to be present in involutions. This appears to be because involutions develop due to frost action on two materials of differing frost susceptibility.

In addition, unless two materials with a contrast are present there is no distinction by which the involuted form can be recognised. Involutions are occasionally developed in a single material when frost action occurs affecting roughly horizontal, thinly bedded sediments with suitable texture. See plates 112 and 116.

A 21 TORS

Tors are relatively common in the area, developed on a variety of rocks. Plate 53 shows an example developed on pegamatitic rocks. Others were observed developed in schistose rocks and in metalimestones. During the course of the study tors were noted but were not studied in detail. Their fairly common distribution in the area is worth noting as they have not been previously reported in the Seward Peninsula.

A 22 PINGOS

In suitable locations pingos were well developed in the area. They were particularly numerous and well developed on the Kuzitrin Flats. This area of low lying poorly drained sediments (see Plate 54) is very favourable for pingo development. Plate 55 shews a rather more accessible example that was seen in a drained thaw lake north of Brakes Bottom.

A 23 STONE PITS

An extremely well marked area of 'stone pits' (circa 1 to 2 m across and up to .75 m deep) was observed, but not investigated in detail, immediately north of the Kruzgamepa River near the road crossing. The site was on coarse alluvial deposits. The spacing of the stone pits was virtually identical to the spacing of the 'large patterns' which may be coincidental or may possibly have greater significance, particularly when compared with stone pit observations in Finnmark.

A 24 CLIMATE OF SOUTH AND CENTRAL SEWARD PENINSULA

The climate around Nome, south of the Kiglu ik and Bendeleben Mountains is subarctic with moderate precipitation. The mean annual temperature of Nome is -3.27°C with the minimum monthly temperature in January or February (see figure 22a). However a mid winter thaw is often experienced in December or January, and then the minimum monthly temperature may be as late as March. Temperatures are above freezing on average from May to Mid September and above 6.1°C from June to mid August. The growing season is therefore only just over two months long. The mean annual range is 25.2°C which is high for a maritime station.

Nome has a higher mean annual precipitation (450 mm) than most of the rest of Seward Peninsula (Teller 288 mm, Candle 270 mm). Every month has some precipitation, but there is a definite 'rainy season' from July to October (see figure 22b).

From the small amount of data available for the rest of Seward

Peninsula the climate inland from Nome might be expected to have a greater range of temperature, with colder winters and warmer summers, and less rainfall.

Hopkins (personal communication) reports that when he and Sigafoos were carrying out the field work for their paper (1951) in the summer of 1948 the patterns appeared more active than they did in 1965. The temperature records for Nome (see figure 22c) seem to offer no explanation for this observation. However 1948 was preceded by a number of years with precipitation above average, whilst 1965 was preceded by a number of years with precipitation below average (figure 22d). Greater precipitation would be likely to be associated with a greater depth of thaw and therefore greater activity of the patterns. However records from other stations in the Seward Peninsula do not conclusively support this suggestion. The reason for greater activity of the patterns in 1948, compared to 1965 is no doubt a very complex one.
Sources:- U.S. Department of Commerce, Climatological Data, Alaska, 1941-48 and 1958-65, Black (1958), Hopkins and Sigafoos (1951).

EAST ANGLIAN SITES AND LOCAL INFORMATION

B.1 GRIMES GRAVES GUN AREA SITE

Grid Reference TL 81059005 Height 75 feet (23m.).

Figure 24 shows the general location of the site and plate 68 shows the general form of the patterns. The surface form and vegetation of the site are described in the main text in section 5.4.An analysis of pattern widths is given in appendix D. Plate 69 shows the excavation in relation to the stripes and plate 70 shows a general view of the section. Figures 25 and 26 are detailed drawings of the section. A number of different materials are present in the section, as described in detail below.

B.11 Materials Found in the Section

In situ Chalk. In the section in situ chalk was present below about 1.9m. The in situ chalk was easily recognised from the numerous well marked bedding planes a few centimetres apart. The bedding of the chalk is almost horizontal at this site. At depth 2.1 to 2.2m there was a thin flint band. Figures 25 and 26 show the way this flint band bifurcates and is interrupted. With one exception these interruptions and bifurcations were clearly solid rock features. The exception was the break in the flint band at 14.95m on figure 25 which seemed to have a displacement of a few centimetres. The in situ chalk exposed in this section contained no large flint fragments.

B.111 Chalk Rubble. Above the in situ chalk, between circa 1.9 and 1.7m, there was chalk rubble. In the lowest parts of the chalk rubble the fragments were rectangular and were simply broken up beds of chalk. Higher up the section the fragments were more rounded, though their shape still frequently suggested they were originally rectangular in form.

B.112 Sand and Chalk Mixtures. All grades from chalk rubble with only a very small amount of sand to sand with only a very small amount of chalk were found. Whilst drawing the section an attempt was made to distinguish between different grades of sand chalk mixture. The grading decided upon was "chalk rubble with low or zero sand", "sand chalk intimate mix" and "sand, low or zero chalk". The middle category (the only true 'mixture' recognised in figure 25) was subdivided into 'more chalky' and 'more sandy'. This subjective subdivision should be examined carefully as the validity of much of the detail seen on the section drawings depends upon these subdivisions. Since it was a purely subjective subdivision made during section drawing no precise figure of percentage of sand and chalk for the various divisions can be given. It is likely that the boundary erred towards a higher percentage of chalk when the general area had a higher percentage of chalk and vice versa where there was a higher percentage of sand. To keep these errors to a minimum frequent visual comparisons along the whole section were made. Plate 71 illustrates the difficulties involved. A comparison of plate 71 and the relevant part of figure 25 gives an indication of how the decisions were made (the section drawing was completed before the photographs were developed). Laboratory analysis suggests that 40% chalk is approximately the division between 'more sandy' and 'more chalky'.

B.113 Sand. This category was easily distinguished. It is notable that there were no sand chalk mixes with very high percentages of sand in this pit. Perhaps 85% sand was the highest.

B.114 Flint. Two different types of flint could be distinguished:

1. Fresh flints. Flints that appeared to be unweathered except for simple fracturing. They were all deeply patinated except on 'fresh' fracture surfaces. Many of these flints were extremely large, commonly with a long axis of 30cm.

2. Weathered flint. Many flints were clearly wind polished, or frost spalled or deeply fretted as if by solution, or some combination of these weatherings. Many weathered flints had a brown, rather than white, patina. The man worked flint should be included here, though it is discussed in detail in Appendix K.

B.115 Allochthonous Stones. Allochthonous stones were relatively rare in this section, and were represented only by a very few (?Bunter) sandstone pebbles, all well rounded.

B.12 Distribution and Relationships of the Materials in the Section

The normal pattern of horizons or strata usually found in soil profiles or geological sections is clearly not present. The materials described in detail above have a definite, though rather complicated distribution in the section. The section can be divided into three areas, though each is intimately related to the others.

B.121 Basal Area - In situ chalk passing up into chalk rubble. At the base of the section in situ chalk was present, with the layer of bedded flint referred to above. The in situ chalk passed up with no perceptible break into the chalk rubble above. In a number of places the in situ chalk had clearly been upheaved (see figure 27 and plate 72). These upheavings were usually immediately beneath a chalk rubble pseudopod (see below). The upheavings were generally beneath the buried ridge form areas and rare beneath the troughs. The chalk rubble zone extended across the base of the whole section. Large flints were fairly common in the upper part of this zone but rare or absent in the lower parts.

B.122 The area of the Buried Ridge Form. The term 'buried ridge form' is purely descriptive and is not intended to imply that this feature was ever 'unburied'. The word 'ridge' alone will be used except where the extended term is needed to avoid misunderstanding.

The materials in the ridge vary from chalk rubble with no sand admixture to sand chalk mix with relatively small amounts of sand. It is notable that the sand chalk mix generally contains more sand near to the base than nearer to the surface. There are a series of upward extending features from the zone of chalk rubble below. These upward extending features have a wide variety of forms. Sometimes the term 'lobe' or 'tongue' could be used to describe the forms. Often they are less regular or more complex and other terms are needed to describe them. The present writer uses the term 'pseudopod' since it perhaps covers a wider variety of forms. Figure 28 shows a series of diagrams of idealised pseudopods and actual examples can be seen on figures 25 and 26 and plates 74 and 75.

Low in the section the boundary between the sand chalk mix and the chalk rubble was usually sharp. This included both the boundary with the chalk rubble zone below and the boundary with the pseudopods. Higher in the section there was a strong tendency for the pseudopods to merge with the sand chalk mix. In the lowest part of the ridge area the pseudopods were narrow relative to the area of sand chalk mix. Towards the top the two are more nearly equal and frequently so nearly merged as to make the drawing of valid boundaries very difficult or impossible.

The pseudopods were fairly evenly distributed across the ridge areas of the section. However, it was notable that in the centre of each ridge there was a very large pseudopod, more than 0.5m wide. (see plates 73 and 74).

So far the description of the section has only mentioned two dimensions. The trough and ridge forms extended in three dimensions, as implied by the terms used. The extra large pseudopods in the centres of the ridges were also continuous in three dimensions (as can be seen by comparing figures 25 and 26 which are sections from opposite sides of the pit). Since it is clumsy to continually refer to the 'characteristic extra large pseudopods in the centre of the buried ridge feature' it is more convenient to refer to them as the 'central dyke forms'. The other pseudopods seen in the section are not so continuous in three dimensions. It was not possible to trace any of these across the pit (only some 1.2m wide). This was either because smaller pseudopods are sinuous in plan or because they are not continuous. The central dyke form varied in size and shape across the section and also was offset, suggesting a sinuous form in plan.

The end section of the pit was aligned at right angles to the contour (see plate 75). It is notable that both the clear pseudopod and the stringer are relatively narrow, suggesting little continuity downslope. The longitudinal section seen in plate 75 was later extended downslope and more pseudopods were exposed. By contrast these pseudopods were wider in section downslope. Excavation of other pseudopods clearly demonstrated that pseudopods vary from being only a few centimetres in downslope extent to a metre or more (excluding the continuous central dyke form). All appeared to approximate to a flattened oval form when sectioned horizontally, with long axis of the oval downslope. The central dyke forms seemed to extend virtually indefinitely up and downslope. It is also notable that the form in three dimensions demonstrated that the pseudopods incline downslope. Plate 75 shows an inclination of 30 degrees, though within 2m other pseudopods inclined at 45 degrees, demonstrating that although there was inclination downslope the amount varies from pseudopod to pseudopod. This variation is not surprising when the variations of cross-section across slope are considered.

In the ridge there were large flints, unweathered except for simple fracturing. These are distributed in a clear relationship to the chalk rubble. As mentioned above, in the chalk rubble zone across the base the large flints were confined to the upper parts. In the ridge form the large flints were generally found in or near chalk rubble pseudopods. They were especially densely concentrated in the central pseudopods as seen in plates 73 and 74. Other concentrations occurred near the bases of pseudopods. Excavation of a central dyke form, and weighing of the material, showed that 63% of the material by weight was flint and only 37% chalk. Even allowing for different densities this suggests that the various drawn sections and plates under represent, rather than over represent, the concentrations of flint in the dyke forms. A character of the flints in the central dyke forms not shown very well in the diagrams or plates is that the flints were very strongly vertically orientated with predominantly long axes vertical and median axes downslope.

The smaller flints in the ridge form were generally very different and with a very different distribution. There were very few small unweathered flints, and these few had a similar distribution to the large unweathered flints. The weathered flints were found only where there was sand mixed with the chalk. In general the sandier the sand chalk mix the more small weathered flints were present, though the quantity was never very large. A bulk sample from a 'more sandy' sand chalk mixture showed only 0.2% particles larger than -2ϕ(4mm).

Allochthonous stones were rare, and in the ridge form were all found in the sand chalk mixture.

The flint implement found in the section is discussed separately in Appendix K. It is sufficient to say here that the implement was found in the north face of the pit at approximately 11 to 12 metres and 1.3 to 1.7 metres depth. It was in an area of sand chalk mix near to a pseudopod. It was definitely in situ in the face and not a later introduction. For the purposes of describing the section the flint implement is merely another 'weathered' flint or perhaps to be considered with the allochthonous stones. Its in situ position in the face was strictly comparable to any other weathered flint or allochthonous stone...

B.123 The Infilled Trough Form. This term is also intended to be purely descriptive. This area was relatively simple. The overall form was a simple trough with some downward complications reminiscent of pipes seen in chalk quarry sections (see figure 25 and plate 76). The bulk of material present was sand with some relatively clay rich areas and some concentrations of flints.

Flint in the troughs was very unevenly distributed, as can be seen in plate 76. Bulk samples varied in stone content from 47% to 10%. Although there were some vague lineations to the flint concentrations no general pattern was detected. All of the flints in the trough were weathered and the largest were very much smaller than the unweathered flints in the dyke form.

Most of the sand in the trough only contained a very small percentage of clay, but some areas had readily discernible relatively high clay concentrations. These clay rich areas were most commonly forming a zone 3 to 20 cm thick adjacent to the sand chalk mix of the ridge areas. The pipe-like extensions of the troughs generally contained clay rich sand. Occasional clay rich areas were found which did not seem related to any special feature. The clay rich areas were recognised visually by their richer brown colour, especially when the soil was moist. In dry weather they were easily distinguished by their tough induration as contrasted to the incoherent sand of the rest of the trough area. Analyses from other sites demonstrates that the clay rich areas are only relatively clay rich, the percentage of clay rarely exceeds 12% and can be as low as 3%. These clay rich areas, particularly when in zones associated with the sand chalk mixture boundary, are referred to by local pedologists as 'clay shift layers'. Better examples can be seen in plate 80.

B.13 Other Features of the Section

B.131 Degree of coherence and voids. During excavation and cleaning of the sections obvious differences of compaction and coherence were noted. The in situ chalk was similar to average soft chalk in its ease of excavation. The sand in the troughs likewise was mainly typical incoherent sand. The materials in the ridge form area, however, were notably extremely compact and needed a pick axe used with considerable vigour to excavate when dry. Although laminations were present in the ridge area all materials were compacted - chalk rubble pseudopods and all grades of sand chalk mix. By contrast the chalk rubble zone below was extremely loose and there were large open voids between the chalk rubble fragments (as marked on figure 25). In many cases the volume of voids appeared to be greater than would be expected if the fragments had been randomly tipped. Some voids contained small lumps of rounded, puddled chalk, others contained small amounts of chalk free sand similar to the sand in the troughs. Clearly some special explanation is required to account for the close proximity of notably compacted material and extremely loose and open material below.

B.132 Laminations. The sand chalk mix in the ridge area was laminated as well as being compacted. The laminations occurred throughout the sand chalk mix of the ridge area but were perhaps best developed between 50 and 125 cm depths. The laminations were 0.2 to 2mm wide sub horizontal spaces in the sand chalk mix, typically 2 to 5mm apart. The laminae were normally sub horizontal though commonly clearly turned upwards at the boundaries with chalk rubble pseudopods, and very occasionally extended across a small pseudopod (see figure 29). Often careful cleaning techniques were needed to expose the laminations, but whenever the trouble was taken to seek laminations in the sand chalk mix they were detected. By contrast no laminae were found in either pure chalk rubble or pure sand.

Topsoil. The topsoil over the section was similar in texture to the sand of the trough areas, with some intimate organic matter. The absence of large stones above the central dyke forms was at first sight problematic. However, when it is remembered that Grimes Graves flint mines are only 300m away, it is likely that large surface flints have been removed by man.

B.2 KNETTISHALL HEATH PATTERN SITE

Grid reference TL 96458045 Height 100 feet (30m).

The surface marking of this site warrants special mention. The area was cultivated during World War II (not very successfully). Air photographs taken immediately post war showed moderately marked patterns. When the site was first investigated in 1964 the patterns were extremely well marked by lines of burnt ground and strips of vigorously growing bracken. The burnt ground had been heather covered and the heather had selectively burned. As the burned ground rehabilitated the patterns became less well marked. It seems possible that when the heather becomes re-established strongly the patterns will again be well marked.

The present writer would describe the patterns on this site as stripes, though with many bars - i.e. they represent the lower limit of stripes, and are not quite short enough to be called elongates (see plates 77 and 78). The average stripe length is just over 50m, giving a length:width ratio of 8:1. Thus this is a useful quantitative type example for the lower limit of stripes.

Plate 79 shows the patterns in relation to the vegetation. Figure 31 shows the main section drawings. The section has many features in common with Grimes Graves. The most obvious difference is that there is rather more sand both in the trough areas and over the buried ridge.

B.21 Materials Found in the Section

In situ Chalk and Chalk Rubble are again present at the base of the section. The chalk at this site is not well bedded and considerable care was needed to distinguish between chalk rubble and the underlying in situ chalk. The horizontal lines shown on figure 31 are purely conventional. The in situ chalk and chalk rubble both contain a few medium sized flints of characteristic dumb-bell shape.

B.211 Sand Chalk Mixture and Sand. These do not differ substantially from Grimes Graves, except in their stone content. Typical analyses for the sand chalk mixture are:

Sand chalk mix - 'more sandy'	24%	Calcium	carbonate
Sand chalk mix medium	29%	"	"
Sand chalk mix 'more chalky'	30%	"	"
Pseudopod material (chalk rubble)	94%	"	"
In situ chalk	98%	"	"

B.212 Stones. Flint - as in the Grimes Graves section the flints can be divided into unweathered and weathered. The weathered flints in this pit included a large number of clearly water rolled pebbles. Allochthonous stones - There was a notably very large percentage of allochthonous stones at this pit (excluding allochthonous flint). Bulk samples showed that allochthonous material was between one third and half of all the stones present.

B.22 Distribution and Relationship of the Materials in the Section

B.221 Basal Area. The depth to in situ chalk was notably greater in this pit than at Grimes Graves Gun Area, being between 2.5 and 2.6m. The depth to in situ chalk is almost the same across the whole section. Particular note should be taken of the fact that the depth to in situ chalk is still the same immediately adjacent to, and between, the pipes below the base of the troughs. The in situ chalk passes upward gradually into chalk rubble.

B.222 The area of the Buried Ridge Form. This area is the same general shape as the ridge form at Grimes Graves. However, when the section was first examined the differences of detail appeared more striking than the similarities. The general nature of material is similar - sand chalk mix and chalk rubble. The sand chalk mixture in this section is much more evenly mixed. Again it is sandier near the base of the ridge area and chalkier near the surface. The chalk rubble pseudopods are much less prominent than at Grimes Graves. They are clearly present, but are often marked by stringers of chalk rubble rather than continuous pseudopods. There is no 'central dyke form' present, though the central pseudopod is larger than the others. The longitudinal section was excavated down the centre of the ridge, and during excavation it was noted that this central pseudopod was persistent down the whole length of the trench.

Figure 31 also shows a section at right angles to the countour. This shows clearly that many of the apparently vertical elements (pseudopods and stringers) are inclined downslope at about 60 degrees to the vertical. The junction between the chalk rubble zone and the area of sand chalk mix above was complex, but a general trend to downslope movement is noticeable. The right hand side of plate 80 also shows a downslope section and the form of the junction again suggests downslope movement. Examination of sections such as that at Knettishall demonstrates how misleading it is to look at features such as pseudopods in only two dimensions.

A feature of this section not seen at Grimes Graves was the lobes of sand projecting into the base of the ridge. An example is seen on the right hand side of the middle ridge form of figure 31, but a larger tongue of sand was seen extending across the base of the ridge of the opposite side of the section (see figure 30). This tongue extended almost to the centre of the ridge and was seen to be continuous for at least 2½m downslope in the longitudinal section. The sand was almost entirely free of calcium carbonate.

The stones were distributed in a similar way to those at Grimes Graves. The unweathered flints were found in association with in situ chalk and chalk rubble. The weathered flint and allochthonous material was distributed roughly in proportion to the sandiness of the materials. No weathered or allochthonous material was found in pseudopods with chalk rubble alone.

B.223 <u>The area of the Trough Forms</u>. The general size of the sand filled trough forms is much larger than at Grimes Graves, though the stripe sectioned was a little narrower. The sand over the buried ridges is deeper. The lower borders of the troughs are extended downwards in well developed pipe forms (see figure 31 and plate 80). Excavations into the latter showed they were circular in plan and hence genuinely pipe form. There were also small pipes extending into higher parts of the ridge areas.

In the lower parts of the troughs there were a number of small isolated areas of chalky material. Nothing comparable to this was seen at Grimes Graves. At first it was thought that these areas were isolated from the main mass of chalky material by decalcification since the pattern became inactive. However, when these patches of chalky material were excavated back into the face they were found to be connected downwards to the chalk rubble below. The connections sloped in the same way as the pseudopods of the ridge area and were sometimes as substantial as pseudopods. Thus it seems that the 'isolated' patches are in fact sections through small pseudopods developed in the base of the troughs (see figures 31 and 32 and plate 80).

The areas of clay rich sand were quite prominent in this excavation (see plate 80 and figure 32). Again they were mainly closely associated with the proximity of chalky material. Figure 32 also shows the distribution of stones larger than 0.5cm in detail. The most notable features are the concentration of stones at 35 to 40 cm depth and the even distribution of allochthonous stones.

B.23 Other Features of the Section

B.231 Voids. In the chalk rubble at the base of the section voids similar to those found at Grimes Graves were present. Some voids were found in the bases of pseudopods, especially the central pseudopod (see figure 31).

B.232 Laminations. Laminations were again found to be present in all grades of sand chalk mix. In general the greater the percentage of sand the easier it was to detect the laminations, though no laminations were present in pure sand.

B.233 Topsoil appeared to be the same as the trough sand, with the addition of some organic matter and leaching of some of the colouration (presumably mainly iron compounds).

B.3 THE DROVE, BRETTENHAM, PATTERN SITE

Location: Grid Reference 914839. Height 118 feet (36m)

Two interlocked sections were excavated across an equiform. The slope at the site of the section was circa 0.5 degrees. Figure 33 shows the form and size of the equiform and figures 34 and 35 show the section drawings. The southern half of the North-South face was not drawn in detail.

B.31 Materials Found in the Section

The same suite of materials was present as at the previously described sites. The in situ chalk was unbedded and it was extremely difficult to distinguish between in situ chalk and well packed chalk rubble. On the section drawing three grades of sand chalk mix are distinguished. Some large and medium sized flints were unevenly scattered through the in situ chalk and chalk rubble. Weathered, including clearly wind polished, flints were present. There were small numbers of allochthonous stones present. This is probably what had lead the Geological Survey to record the area of the site as 'Boulder Clay' in 1884.

B.32 Distribution and Relationships of the Materials in the Section

B.321 Basal Area. Again chalk rubble and in situ chalk were present across the base. Because of the difficulty of distinguishing between in situ chalk and compact chalk rubble certain parts of the section were taken down to 3.5m. The depth to in situ chalk seems to occur at circa 2.25 to 2.6m, but these figures are not particularly reliable.

B.322 'Buried Ridge Form'. Since this is an equiform the buried ridge form seen on the sections is really a buried flattened dome in three dimensions. A feature of this section is that the pseudopods tend to bifurcate into two curving portions. When these were excavated back into the section the two 'arms' of the pseudopod were found to be the sides of a hollow hemispherical, or cup shaped, form (see plate 83). There was no marked trend for the pseudopods to incline downslope (N.B. the slope was only ½ degree). There was no particularly large pseudopod in the centre of the pattern. The sandiest grade of sand chalk mixture was again clearly at the base of the section. Distribution of weathered and unweathered flints was similar to that at Grimes Graves and Knettishall.

B.323 Infilled Trough Form. The troughs were similar to those seen at previous sites. Sand with notable clay content was again most common adjacent to chalky material. A very well marked feature was the presence of small pseudopods in the lower parts of the troughs. These were generally narrow with a lobate upper termination.

B.33 Other Features of the Section

B.331 Voids were again present in the chalk rubble across the base at somewhat variable depths between 1.6 and 2.25m. There was no noticeable trend for the voids to be deeper at any particular part of the section.

B.332 Laminations were common throughout the areas of sand chalk mixture.

B.333 Topsoil. The topsoil here was complex because the area had been deep ploughed about four years before. There were still very clear ploughing structures in the top 35 cm - this layer is shown conventionally on the section. The ploughing carried some sand chalk mixture over the top of pure sand and vice versa. This probably affects the areas of vegetation marking the patterns, though in fact little evidence of such an effect was seen.

B.4 OTHER FIELD INVESTIGATIONS

Obviously during the course of two years' work in East Anglia many sites were visited in the field. To avoid unnecessary repetition only a selection of field observations on minor sites will be recorded here. A few further examples are recorded in the main text.

B.41 Babraham

Grid Reference TL 510513 Height 110 feet (35m)

At this site a particularly long section of patterns was exposed during the course of road improvement. Figure 45 shows the position of this section and the patterns of the general area as mapped from a number of air photographs (3 sets of cover). On no set of air photo cover were the patterns in the area of the section very well marked. As far as could be determined the patterns shown in the section were medium to long elongates. The section showed buried ridge forms of sand chalk mix with chalk rubble pseudopods and troughs of sandy material (see plates 84 and 85 and figure 36). The general appearance was similar to that of the three main sites described above. The section was cut across a spur so that at the East South East of figure 36 the patterns crossed the section at right angles, whereas at the other end of the section the patterns crossed the section obliquely. The main feature of interest was the demonstration of the variations that occur within a single section when a large number of patterns are observed. Variations in the size, shape and area of the trough forms, variations of the width of the ridges and variations of the pseudopods all occur within a short distance. The materials were very similar to those described from previous sections except that the sand in the troughs was generally more clay rich, as was the general texture of the soil of the surrounding area. This relative abundance of clay may well explain why the patterns of this area were poorly marked on the air photographs.

An unexplained feature of this section, seen in no other section, was a meandroid plane running across most of the section, with the appearance of 'stylolites' reported from sedimentary rocks.

B.42 Euston

At Euston Lime Quarry, Grid Reference TL 896774, Height 125 feet (38m), (see figure 43), sections through patterns were exposed in the quarry faces. These were closely similar to the patterns previously described. Air photographs of this area, taken specially for this study, show clear stripes between the quarry and the nearby Fakenham Spinney (plates 88 and 89). These stripes are notably straight with no bifurcations, probably because the valley side is a simple planar slope. Measurements showed a mean width of 6.48m, standard deviation 0.41m and a range from 5.5 to 7.25m. This range on such a uniform slope should be particularly noted. On the crest of the ridge well marked equiforms could be seen. In a sample of 20 the mean equiform diameter was 8.7m, standard deviation 1.83 and the range was from 6.6 to 13.4m. (for fuller details see Appendix D).

The stripes were also seen on the ground at certain seasons. Plate 90 shows Fakenham Spinney and surrounding fields in June 1964, with the stripes showing clearly in barley at varying growth stages. Plate 91 shows almost exactly the same view in April 1967 when no stripes were visible at all in young barley. Many patterns in East Anglia showed at certain seasons and not at others, and this is not an exceptional example. The farmer of this land (and adjoining areas of extensive patterning) stated that the patterns appear in the crop as soon as there was any moisture shortage in the soil. In many years yields on the different parts of the pattern are markedly different.

B.43 Cockley Cley and Swaffham

An account of this small area is included as a typical description of an attempt to follow up air photograph observations in the field. Swaffham Golf Course (A on plate 92) showed very well marked patterns, both in the 'rough' and on the 'lanes'. In the 'rough' the patterns were marked by the contrast between heather and a grass-herb association. On the 'lanes' the patterns were picked out quite well by variations in the species of herbs present amongst the grass. Augering was unsuccessful due to abundant stones. At 'B' the original air photos showed well marked equiforms on the hill crest and stripes on the slopes to the north and west. The area was under young barley when visited. Despite climbing 30 to 40 feet in several trees no trace of patterning was seen. On the old rifle range at Cockley Cley Heath ('C') good examples of vermicular meandroids were seen on the air photos. These were not visible on the ground, though the farmer reported that they became visible in barley "after only 2 or 3 days of drought". At Swaffham Heath well marked stripes on a south east facing slope were seen on an adjoining air photo. When investigated on the ground it was found that the slope had been divided into three parts for cultivation. The lowest third of the slope had been left fallow and showed no patterns at all. The middle section of the slope, covered with immature barley showed well marked patterns when viewed from 30 to 40 feet up. On the upper third of the field no patterning could be seen from a height (good perspective angle) but patterning could be seen when looking at the side of the crop from denser and less dense leaf growth of the barley, at regular intervals across the slope.

B.44 Structures seen at Garboldisham

Grid Reference TM 006815.

150m east of Garboldisham Inn a fresh road cutting in 1963 showed some structures of a type not previously recorded in the British Isles. These structures were developed in a section showing about a metre of stony sand overlying till (see plates 109 and figure 49). The till contained large particles of chalk, flints, sandstone and shale - many of the stones were striated. The matrix was a stiff olive coloured clay. The whole till appeared identical to typical sections of Chalky Boulder Clay with Jurassic matrix. This till is typical of the Lowestoft Glaciation in this area (Baden-Powell 1948). The orientation of the stones in the till was determined and the result is shown in figure 92a. The stone orientation was taken at the base of the section. As far as could be judged this was below the level of any later disturbance. West & Donner (1956) identify the tills of East Anglia from their stone orientation. When the stone orientation direction determined at the Garboldisham section is plotted on the diagrams of West & Donner it seems to confirm that this is a Lowestoft Till, possibly Lowestoft Stage I. 50 to 70 m west of the section the till could be seen to overlie sand.

The structures of particular note in this section are sand filled hollows at regular intervals in the upper surface of the till. These sand filled hollows run backwards into the face at right angles to the local contours. These hollows were joined by arcuate bands of sand, again continuing into the face in three dimensions. The sand filling these hollows, and in the arcuate features, appeared identical to the sand above except for the absence of stones. There were some 10 to 12 of these features spaced at about 3m intervals along the face. The section was later viewed by some members of the Quaternary Discussion Group, Cambridge, but could not be explained at this time. One suggested possible mechanism was as ice push features. The origin of these features is discussed in the main text, though it should be noted here that there is a striking similarity between the features of plate 109 and plate 26.

B. 5 SUMMARY OF THE PLEISTOCENE DEPOSITS OF EAST ANGLIA

Since chronology and interpretation of deposits are mentioned at several points in the section on East Anglia the following brief description is included to provide a background. The Table given in the main text summarises the Pleistocene succession in East Anglia.

The climatic fluctuations identified from the Crag deposits are of little significance to the subject of this thesis, likewise the Cromerian stage. The deposits of the Lowestoft Glaciation in East Anglia are divided into three parts - the North Sea Drift (which includes the Cromer Till), the Corton Sands and the Lowestoft Till proper. There are a number of problems concerning the interpretation of the North Sea Drift and the Corton sands (vide particularly Boswell 1931, Solomon 1932 and 1935, West and Donner 1956 and West 1961 and 1963). However, since these deposits do not occur in the main area of patterned ground these problems will be ignored. Deposits of the Lowestoft Till proper are found in many localities throughout East Anglia. In much of East Anglia the matrix of the till is a dark coloured mixture of sand and Jurassic Clays. The commonest erratics are chalk, flint, Jurassic rocks and fossils, sandstones, quartzites and quartz - much of the latter two probably mainly from the Bunter (Baden-Powell 1948). This till is referred to by Baden-Powell as the dark boulder clay. In more northerly parts of Norfolk the Lowestoft

Till has a more chalky matrix (Baden-Powell 1948, West 1961).

The Hoxnian interglacial deposits are only of interest to this study in that they provide dating evidence and evidence of climatic change.

The deposits of Gipping Till are also described from many localities in East Anglia, though evidence of actual tills seems to be lacking in the area south of the Cromer Ridge and north of Norwich (see Solomon 1932, Baden-Powell 1948, West 1961 and 1963). Baden-Powell (1948 p.285) describes the Gipping Till as follows: "The matrix is a mixture of chalk and sand, with some pale brown clay, and the erratics consist of flint, hard and soft chalk, Red Chalk (common), Bunter sandstones and quartzites, porphyrites of old Red Sandstone types, various feldspathic grits ... (and possibly rhomb porphyry). Rarer Jurassic fossils, basalt .... are believed to be derived from the earlier Lowestoft Boulder Clay. The pale boulder clay weathers quite differently from the dark into an unbedded unsorted boulder gravel, of which the matrix is usually highly ferruginous".

The deposits of the Ipswich interglacial are again only of interest to this study in that they provide dating and climatic evidence for the general East Anglian sequence.

During the Weichsel the ice sheets only just reached the East Anglian coast. The till (Hunstanton Till) is only found up to 100 feet on the north coast of Norfolk (see especially Suggate and West 1954 and Straw 1960).

The age and directions of movement of tills in East Anglia have been mainly identified by the erratic content, the nature of the matrix and from till fabric analysis (see especially Harmer 1928, Baden-Powell 1948, West and Donner 1956).

APPENDIX C

STUDIES IN NORTHERN SCANDINAVIA

C. 1 STANGVATNET AREA

69° 42' North 12° 52' East. Height 530 - 565 m.

C.11 Features Investigated. Well marked meandroids and less well marked elongates and stripes were seen on air photographs (see Plates 120 and 121). Three areas of patterning were investigated on the ground (see Plate 121). Area I on the air photograph shewed clear meandroids on a level hill crest. On the ground these were found to be well marked equiforms. Area II had poorly marked meandroids on the photo and barely any pattern at all could be distinguished on the ground. Area II was an apparently identical site to Area I. Areas III and IV shewed poorly marked stripes and elongates both on the air photographs and on the ground. Areas I and II were separated from Areas III and IV by areas of steep slope with no patterning at all. Figure 50 shews the relationship of the four areas to relief. The system of site numbers used in Scandinavia was to use the index number of the appropriate 1:100,000 map sheet as a prefix - in the example below sheet U5 - and then to add a sub letter for each site on the map sheet.

C. 12 Site U5D was in area I described above. Clear equiforms were seen on the ground (see Plate 122). Sizes of equiforms ranged from 5.5 to 7.5 m. The equiforms had large flat centres and fairly narrow trough like margins ('sharply raised centre type' - see figure 19). The total relief varied from 25 to 50 cms. All of the equiform centres had some bare soil areas, presumed to be frost scars. These scars were generally 0.5 to 1.5 metres across and commonly all over the equiform centre or grouped in a circle (see figure 51). In many cases there was a clear impression that the middle of the central area was not as active as the periphery, as in figure 51a.

A section some 1.2 m deep was blasted across a well marked equiform. Figure 52 shows a plan of the equiform and figure 53 and Plate 123 shew the section. This section was remarkable for its dryness and ease of excavation, unlike most tundra patterned ground sites. As a result an unusually clean section was cut shewing material that appeared much lighter in colour than usual. The composition of the materials was the typical silty material similar to that usually found at large pattern sites (see Appendix E). There was a detectable decrease in siltiness from the base of the section upwards, though the mechanical analyses shew that the decrease in siltiness was only from 67 to 57 per cent. The structures can be seen so clearly on plate 123 and figure 53 that little description is needed. Large stones were found mainly under the trough areas. On the left of the section tongue forms can be seen curving in from the trough area. On the right of the section there is an unusual wedge shaped tongue originating from the flank of the central area and again curving towards the pattern centre. No voidal area was seen, despite very careful search under very favourable conditions, though the material might not be suitable for preservation of a voidal area.

C. 13 Site U5B was in the area marked IV on Plate 121. In this area there were moderately and poorly marked stripes and elongates. Careful examination of the air photos shewed that the elongates and stripes were of two different widths. On the ground the mean size of the larger ones was found to be 3.64 m and the range between 2.9 and 4.55 m. The mean of the smaller elongates or stripes was 1.58 and the range between 1.4 and 1.85 m. These were all parallel to one another on the same site, with no apparent variation of the general site characteristics. Close examination shewed that some of the larger patterns were dividing along their centres to become smaller stripes (see figure 54a). The surface appearance of the larger patterns was notably degenerate whereas the smaller stripes were very clearly marked. A section was dug through a small stripe (see figure 54b). This section was very similar to the sections seen on Magerøy (see figures 68 and 69). The unusual distribution of stones in this section was notable.

C.14 Sites U5A and U5C were both in the area marked III on plate 121. The patterns on this site were moderate or poorly marked elongates or stripes (see Plate 124). The stripes were 3 to 3.5 m wide and had a relief of circa 20 to 30 cms. Much of the patterned area had open water pools in the marginal depressions, which contrasted strongly with the nearby U5D site described above. The patterns were vegetated all over with only occasional frost scars, with most frost scars in the wettest areas. The vegetation of the margins was mainly birch and willow. On the centres the vegetation was generally lower but birch and willow were still fairly common. The patterns were degenerate in appearance. There were some signs of division of a number of the stripes in a similar way to that described for site U5B above.

Pit U5A was blasted across two elongates, towards the upslope edge of the patterned area where the slope was 5^{o} and the site was slightly better drained. Despite the somewhat better drainage the excavation conditions were particularly difficult. Figure 55b records the section observed. During the cleaning of the central 'dyke form' of peat a number of stones were removed which were clearly vertically orientated.

There were some signs that the whole of the excavation shown in figure 55 was once one pattern that has now divided into two separate elongates (note particularly the plan form of the two elongates).

This would suggest elongates circa 7 m wide had divided to form the present 3.5 m width elongates.

An attempt was made to blast a further section in a poorer drained part of the patterned area (site U5C), but flooding and flowage of the silty materials prevented any observations being made.

C.15 Observations on the Patterns and Snow. The investigations in the Stangvatnet area were carried out late in the season (second week in September). About 7.5 cm of snow fell on the last night spent at this site. Within six to eight hours after the snowfall the snow had melted completely over bare soil but not at all over vegetation (see Plate 125). This may indicate two important factors in pattern formation. Firstly it is a measure of relative rates of heat loss from the two different parts of the pattern. Secondly it also suggests that under certain conditions the heat loss from the vegetated area may be further retarded by a snow cover, whilst the scar areas remain bare. Drifting snow may accentuate this difference, by the drifting snow being trapped in the vegetation, though on the occasion recorded little drifting was evident.

C. 16 Preliminary Interpretation. A very important observation at this site was the clear vermicular meandroids on air photographs being seen to be clear equiforms on the ground. The explanation is that not all the marginal depressions were equally well marked and thus only parts of the equiforms were visible on the photographs, giving a 'vermicular meandroid' appearance (see figure 56). Another important observation was the apparent division of larger stripes into smaller ones. Some larger patterns showed no signs of dividing, and equally some smaller patterns showed no signs of ever having been larger patterns.

The problems of deciding whether patterns are actively forming and developing, just showing some activity, or completely inactive have already been discussed in relation to the Alaskan patterns. The general appearance of the vegetation suggested that the larger patterns were not actively forming. The frost scars may well only indicate subsidiary continuing activity. The signs of division of the larger patterns suggests that the larger patterns are no longer in balance with the environment. The smaller stripes are even more difficult to assess for activity as they do not seem ever to have frost scars and are primarily relief patterns. The clarity and regularity of their appearance in the majority of cases suggested that they are in balance with the present environment.

C. 2 KISTRANDFJELL

Location: 70° 28' North, 14° 28' E. Height 250 m.

C.21 The General Site. The site is near the west shores of Porsanger Fjord, on a promontory just south of Russenes (see Plate 126).

Because the patterns at this site show certain special features it is necessary to describe some site characters in greater detail than normal. The underlying bedrock, dominantly mica schist, dips gently to the south, and has a well marked east-west jointing. Stripped bedrock surfaces, striations of both bedrock and boulders and plucked surfaces indicated that the whole site had been overridden by ice. The ice movement at this site was South to North (Holtedahl & Andersen 1960), resulting in plucking which emphasised the east-west jointing and left a series of stepped bedding surfaces. The 'risers' of the steps run east to west across the hill, parallel to the joints and the 'treads' slope gently towards the south south west, parallel to the bedding (the bedrock in this area is highly metamorphosed and the 'bedding surfaces' referred to might be other planes of weakness - this is not important to the description or the effects of the bedrock planes on the patterns). Where the patterns were present the bedrock was overlain by silty till or possibly till with loess mixed in by frost action.

C. 22 Features Investigated. The patterns were first identified on air photographs. On the ground the patterns were found to be in lineations of unusual type on the north and west flanks of a hill summit. Across all the area the lineations are approximately east-west (see Plate 127). Thus on the west facing slope the patterns were elongated downslope, similar to the usual stripe form. On the north slope the patterns were elongate across slope (parallel to the contours). On the north west facing slope the features were linear at an oblique angle to the slope. Figure 57 shews these lineations diagrammatically. This observation may well be of fundamental importance to the understanding of patterned ground generally.

C. 23 Patterns with a Westerly Aspect. These appeared to be fairly normal stripe and elongate forms in most respects. They were marked by birch vegetation on the margins and either bare ground (frost scar) or low grass and herb (vegetated frost scar) centres. The margins were also in part marked by troughs and sometimes concentrations of stone. Thus these patterns were marked mainly by vegetation, with relief and stone as subsidiary features. Large, absolutely bare frost scars were extremely common and the patterns appeared to be very active. The patterns were developed on slopes up to 10 degrees or more, but still tended to be large elongated frost scars in a train, rather than continuous stripes. The individual elongate frost scars were separated by step like fronts (see Plate 128 and figure 58). Two sections were blasted across these stripe or elongate forms. The first section was across an elongate some 6 m wide (see figure 59 and Plates 129 and 130). Under the margins there was a relatively deep layer of peat.

The rest of the section was mineral soil. Beneath the peat of the margins and near to the margins the mineral soil was brownish, whereas under the pattern centre there was much paler mineral soil, broadening with depth. The matrix of the mineral soil was silty sand in the browner areas (dark brown Munsell colour) and sandy silt in the paler areas (olive). The whole of the mineral soil was very stony. Nowhere in the pit was any notable orientation of stones detected, nor was any voidal area detected. There were, however, notable concentrations of stones under the peat margins (see Plate 129).

The second section was excavated a short distance away across a narrower stripe-elongate in the same series. The plan and section are shown in figure 60. The materials in this section were similar to the section described above. Although the section was excavated to 1.3 m no bedrock was reached, nor were any voidal areas seen.

Some 50 m downslope from the larger excavation a small pit was excavated to investigate one of the step fronted scars in a stripe-elongate. In particular it was hoped to determine whether or not this feature was similar to a small solifluction lobe. Plate 131 and figure 61 shew the section excavated. Figure 92b shews the orientation of stones in the step, dominantly perpendicular to the step face, which is very different from the stone orientation in a solifluction lobe.

C.23 Patterns with a Northerly Aspect. The patterns on the north facing slope were steps which were narrow downslope and broad across slope in contrast to the stripes on the west facing slope. The steps had bare soil (frost scars) on the treads and well vegetated risers (see figure 62). The scars had treads that were similar to those of Plate 131, and an excavation revealed similar features. Some steps had stones projecting perpendicularly from the faces of the risers. Many of the risers had a 'turf roll' form (see Plate 6).

C. 24 Patterns with a North-Westerly Aspect. Here the patterns were represented by lines of frost scars trending obliquely across the slope. These scars were steplike in TWO directions. Between individual scars in any lineation there were often small step like features. On the 'downslope' margin of any one lineation (i.e. the North margin) the lineation generally had steplike side forms (see Plate 132 and figure 63). These patterns were intermediate between the stripes on the west facing slope and the steps on the north facing slopes. They clearly combined elements of both and passed laterally into both forms. This form of patterned ground has not been previously recorded.

C. 25 General Note on the Depth to Bedrock. The depth of bedrock was not determined in any section, the deepest section being 1.3 m. Occasionally what appeared to be bedrock was seen at the surface where there was a slightly steeper local slope. Many large autochthonous boulders were found on the pattern areas. The suggestion is that the bedrock is not very deep beneath the patterns, as the general appearance on the air photographs also indicates. This point was, however, not proved.

On the summit of the hill the patterns were replaced by numerous small frost scars, a feature which in many other areas was found to be frequently indicative of bedrock at shallow depth.

C. 3 BILLEFJORDFJELL

The general geological and soil conditions are very similar to those at Kistrandfjell, some 17 km to the north. A number of features were investigated briefly.

A series of steps were seen on a slope of 13°, aspect 103° (see Plate 133). These steps were marked by bare soil on the treads and a dense vegetation of dwarf birch and heaths on the risers. A section was excavated across one step. Solid rock was found below the bare soil area and thick peat below the riser and just downslope of the riser (see figure 64). A nearby step with similar bare soil tread and well vegetated riser was seen to pass laterally into a step in the bare rock (see figure 65 and Plate 134).

On a flat summit a distribution of frost scars reminiscent of the elongation relationships at Kistrandfjell was seen (see figure 66). Patterns elongated downslope were present on the west facing slope, scars elongated across slope were present on the north facing slope, and equiform scars on the flat area, all within a distance of 20 or 30 m..

An area of large frost scars which did not form a definite pattern were seen near the summit (see Plate 135). These were not exceptional in their development, but were exceptionally well placed for photography. Similar large frost scars are fairly frequently present on the exposed hill summits in this region.

Steep sided peat hummocks were fairly common on the west slopes of Billefjordfjell. These were equiform in plan regardless of slope. They consisted of thick peat overlying either a solid rock core or a mineral soil core as in Plate 136. There was no difference in surface form between rock and mineral soil cored hummocks.

C. 4 PATTERNED GROUND OF MAGERØY

The patterns of Magerøy were investigated without the aid of air photographs which made the work much more difficult, and prevented many general interpretations. Two types of patterns were observed. Large poorly integrated frost scars were common on hilltop areas. The hills are low and rounded and many give the impression of some sort of solifluction sheet flowing off in all directions. Most of these apparent solifluction sheets had frequent frost scars of all sizes which did not seem to be in any integrated pattern, though they might be when viewed on air photographs.

Very regular stripes were seen in a number of localities. These were termed 'medium sized' patterns as they were about 1.5 m wide (see Plate 137). They were marked by relief, with a central ridge and marginal trough, both of equal proportions, and a total amplitude of relief of about 30 cms. An area of these patterns was investigated in detail at 71° 4' N, 15° 3' E, height 195 m, slope 6°, aspect 190°. Detailed botanical investigation shewed that there were differences of species and abundance across the pattern (see figure 67), though these vegetation differences did not noticeably aid the visual distinction of the patterns. Two pits were excavated and some sections also cut backwards to give some ides of three dimensional form. The cross sections all showed the same general features (see figures 68 and 69). A weathered slate or schist was found at 35 - 40 cm beneath the patterns. Peat was found continuously across the surface, some 5 to 10 cm deep over a silt rich mineral soil. Beneath the centre of the ridge there was invariably a pillar (or dyke form in three dimensions) of peat which spread sideways at depth. Sometimes the sideways extensions met the surface peat again near the bottom of the troughs, sometimes the extensions faded out, or were curled backwards on themselves. No voids were seen.

A section was excavated on low ground, on a favourable site, purely to attempt to find permafrost. The excavation was abandoned at 1.5 m and neither permafrost nor a voidal layer was found. A voidal layer was observed in a pit cut for road fill. The material was mainly small slate or shale fragments with silt in the upper layers, and shewing evidence of downslope mass movement. A voidal layer was seen at about 70 cm, and also laminations above.

Larger forms of patterned ground have been reported from Magerøy (Kallendar 1967). Kallendar reports in detail on the patterned ground forms near Nordkap and in particular mentions that 'earth hummocks', similar to those described above, are common throughout Magerøy, particularly on lower ground. He emphasises that there are great difficulties in classifying the observations on the island because of the many transitional forms, especially transitional forms from patterned ground to solifluction lobes. He mentions solifluction lobes that are aligned obliquely across slopes for unexplained reasons. Another interesting report by him was the description of 'non-sorted' patterns passing laterally to patterns that might be regarded as sorted.

C. 5 SENNELANDET VALLEY

Patterns were investigated near the watershed between the Sennelandet Valley and Stockdalen, at 70° 10' N, 13° 1' E. The patterns were similar in appearance to the medium sized relief patterns investigated on Magerøy (see Plate 138). The average widths varied from 1.5 m to 2.3 m on different parts of the site. As on Magerøy, there were detectable but not obvious differences of vegetation. However, the form of the pattern sections was differenct from that seen at Magerøy (see figure 70). The mineral soil was sandy silt. On flatter sites the stripes were seen to give way to equiforms with diameters of approximately 2 to 2.5 m.

On steeper slopes in the Sennelandet Valley occurrences of solifluction lobes and indistinct patterning were seen in oblique lineations across the slopes. These lineations were seen to be parallel to the dip of the underlying rocks. Kallendar (1967) reports, but is unable to explain, similar occurrences on Magerøy. In the examples seen in the Sennelandet Valley the lineations are undoubtedly controlled in some way by the underlying bedrock.

C. 6 <u>OBSERVATIONS NEAR SUNDHEIM</u>

Location 69° 2' N, 7° 46' E, Height 100 m.

Many relief equiforms (earth hummocks) about 1.5 m diameter were seen, over a large area of light woodland (see Plate 139). The hummocks were covered by fairly lush vegetation and in a number of cases trees were growing from the centres of the hummocks. In section there was brown silt overlying laminated grey sands and fine gravel at 1 m. The most striking feature of the section was a leached layer of silt which was markedly crenulated (see Plate 140). Extremely well marked leached layers are common in this region, since the high rainfall and generally low temperatures favour podsolisation. However, the crenulated leached layer seen in plate 140 is not a normal podsol feature. The crenulations are probably due to frost action, though the general vegetation of the site at present suggests that the patterns at most are only 'ticking over'.

C. 7 <u>KVAENANGSFJELLET</u>

Location 69° 54' N, 21° 33' E.

A section was excavated in an area of medium width stripes and revealed very similar form in section to that of the relief equiforms near Sundheim.

C. 8 <u>YTRE GARADAK</u>

70° 16' N, 14° 22' E, Height 5-40 m.

Patterns at this site were first distinguished on air photographs (see Plate 141). On the ground patterns of several sizes were found, which will be described separately.

C. 81 <u>Large Patterns</u>. The large, obvious north-south aligned elongate pattern forms that are seen on plate 141 were easily distinguished on the ground. They were marked by alternate strips of birch bushes and areas with lichen and bare ground (see Plate 142). The bare ground was exceptionally stony with no fine soil visible. The stones were all well rounded, and from the relationships to surrounding features the whole area was undoubtedly a beach at some time after the last glaciation. The stripe width was rather more variable than usual (see Appendix D, Table D4a).

The surface distribution of the patterns was unusual. Almost all the patterns were elongated north-south, even on an east facing slope. Elongate forms were found to continue across minor cols and a short distance down north facing slopes. The birch was in the 'centre' of the elongates, rather than around the margins as seen at all other sites. The birch in the elongates had been clearly affected by the wind. It was leaning away from the south, and was much lower on the southward ends of birch areas.

A section was excavated across a pattern (see Plate 143 and figure 71). The material in the section was almost entirely pebbles or coarse gravel. Only occasional 'piles' of fines were found on top of some of the large stones deep in the section, suggesting that there may have been more fines at some time in the past. The main bulk of the material in the section was very definitely not frost susceptible. The major features of the section seemed to be entirely accountable to undisturbed normal soil development.

C. 82 Small Patterns. Several sets of small patterns were investigated at this site (see Plate 144). This was the only site seen in Finnmark where this size and form of pattern was found. The patterns were marked by narrow lines of vegetation and stony areas, with or without fines. Three variants of section were seen (see figure 72). In a number of cases there were peaty extensions downwards from the vegetation areas and curving under the central area (see figure 73 and Plate 145).

C. 83 Very Small Patterns. Both stripes and equiforms, about 15 cm across (miniature zellenboden size) were also seen on this site in similar materials. The only site excavated had bedrock only 5 cm below the surface (see figure 74).

APPENDIX D

PATTERN SIZES AND RELATION OF FORM TO SLOPE

TABLE D1 PATTERN SIZES - ALASKA - FIELD MEASUREMENTS

Site Number	Mean	Standard D Deviation	Range	Number of Observations*
		Equiforms (metres)		
X4	8.90	.96	7.5-10.6	6 x 1
X4	7.65	1.03	6.5-9.5	8 x 1
X4	8.18	1.44	6.5-10.6	14 x 1
H1**	5.0-6.0	-	-	-
T1**	7.0-8.0	-	-	-
		Large Elongates and Stripes (metres)		
C2	6.5	-	-	1 x 1
C8	6.0-6.5	-	-	-
D5	6.0-6.5	-	-	-
X34	6.6	-	-	3 x 1
X4	5.6	-	-	1 x 4
T1**	5.0	-	3.0-6.0	-
		Miniature Stripes (cms)		
X32	16.5	-	13-20	2 x 5
X33	15,6	2.72	11.5-20	14 x 1

* Where the figure in this column reads 12 x 1 then 12 single measurements were made. Where it reads 3 x 6.6 then 3 cumulative measurements, with an average of 6.6 patterns in each measurement, were made.

** Sites in Central Alaska.

This table is limited because much data was lost by theft. However, the figures for the Seward Peninsula given above are not an abnormal sample.

TABLE D2 PATTERN SIZES - EAST ANGLIA - FIELD MEASUREMENTS

Site Name	Mean	Standard Deviation	Range	Number of Observations*
	Stripes (metres)			
The Drove, Brettenham	7.1	.57	5.8-8.1	18 x 1
Eriswell High Warren	7.0	-	-	1 x 8
Fakenham Spinney	6.9	-	-	1 x 6.5
	8.62	-	-	1 x 6.5
Grimes Graves	6.98	.84	5.5-8.9	16 x 1
	6.13	.59	5.6-7.7	11 x 1
	7.92	1.29	6.7-10.1	5 x 1
	6.46	.85	4.9-8.2	18 x 1
Knettishall Heath	7.1	-	-	1 x 4
Thetford Heath	6.43	.86	5.2-7.7	6 x 1
	7.77	1.02	6.1-10.2	22 x 1
	7.26	.88	6.1-8.7	17xx 1
Weather Heath	7.5	-	-	4 x 1

* See footnote table D1

TABLE D3 PATTERN SIZES - EAST ANGLIA - AIR PHOTOGRAPH MEASUREMENTS

Site Name or Grid Reference	Air Photo Scale	Mean	Standard Deviation	Range	Number of Measurements*
		Equiforms(metres)			
Congham Heath	1:10,400	10.4	.50	7.1-13.5	20 x 1
The Drove,Brettenham	1:1,640	10.2	1.67	7.5-12.2	10 x 1
Fakenham Spinney	1:4,350	9.6	1.92	6.9-13.4	10 x 1
	1:4,430	8.0	1.17	6.6-9.6	10 x 1
Risby Poors Heath	-	8.9	-	-	4 x 1
922753	-	10.2	-	-	-
933754	-	7.9	-	-	-
		Elongates and Stripes (metres)			
Barnham	-	6.6	-	6.1-7.0	-
Congham Heath	1:10,420	7.8	.80	6.7-9.1	10 x 8.3
The Drove, Brettenham	1:1,030	7.6	-	-	3 x 6
	1:980	7.3	-	-	3 x 6.6
	1:1,010	6.7	-	-	3 x 8
summed	-	7.2	1.44	6.0-8.3	9 x 6.9
Fakenham Spinney	1:4,350	6.7	.68	6.4-7.0	5 x 5.8
	1:4,400	6.4	.46	5.9-7.1	5 x 4.8
	1:4,430	6.3	1.52	5.5-7.3	5 x 4.4
summed	-	6.5	.41	5.5-7.3	15 x 5.0
Grimes Graves	1:2,400	7.0	.76	6.5-8.2	10 x 9
Icklingham(E of)	-	5.1	-	-	1 x 16
Icklingham(NE of)	-	6.5	-	-	1 x 9
Knettishall Heath**	1:4,300	6.8	.47	6.2-7.7	12 x 7.1
Rushford/Euston Park	1:1,000	7.4	.85	6.1-8.2	5 x 6.6
Thetford Golf Course+	1:8,340	7.0	.90	5.3-7.9	5 x 4.8
Thetford Heath	1:10,200	7.8	1.12	6.5-9.2	14 x 6.6
	-	6.3	-	-	-
816721	-	8.0	-	-	-
858783	-	6.2	-	-	-
870781	-	7.8	-	-	-
876783	-	7.0	-	-	-
910981	-	7.2	-	-	-

* See footnote table D1

** Near limit of stripes(see plate 78)

\+ Patterns marked by differential tree growth (see section 5.9)

TABLE D4a PATTERN SIZES - SCANDINAVIA - FIELD MEASUREMENTS

Site Number	Mean	Standard Deviation	Range	Number of Observations*
		Equiforms (metres)		
Q7A	1.5	.28	1.2-2.0	20 x 1
U5D	6.37	.77	5.5-7.4	6 x 1
U5E	-	-	3.0-5.0	-
U6A	-	-	5.0-7.0	-
V3B	4.55	1.05	2.7-6.1	12 x 1
1734/I/A	-	-	1.5-2.0	-
1734/IV/A	-	-	2.5-4.0	-
		Elongates and Stripes(metres)		
U4A	1.94	.28	1.6-2.3	3 x 7
U5A	-	-	2.0-3.0	-
U5B +	3.64	.66	2.9-4.6	5 x 1
U5B ++	1.58	.05	1.4-1.9	6 x 1
U5E	-	-	3.0-4.0	-
V3A	-	-	1.5-2.0	-
V3B	3.43	.69	2.3-4.7	12 x 1
V3D	5.08	.66	3.9-6.4	10 x 1
V4B	.56	.04	.36-.80	12 x 1
W1A	1.34	-	1.3-1.4	3 x 1
W1B	1.48	-	-	2 x 8.5
	1.50	.15	1.3-1.8	8 x 1
1734/I/A	1.50	-	-	-
		Unusual Stripes (metres)		
V4B	5.16	1.89	1.5-8.4	21 x 1
	5.36	1.60	3.6-8.2	5 x 1

* see footnote table D1

\+ Un-divided patterns ++ Divided patterns.

TABLE D4b COMPARISON OF MEAN PATTERN SIZE AND FORM - SCANDINAVIA

	'Large'	Medium	Small	Unusual
Equiforms	4.55 6.37	1.5	-	-
Elongates and Stripes	3.43 3.64 5.08 5.36	1.34 1.48 1.50 1.50 1.58 1.94	.56	5.16

TABLE D5 PATTERN SIZES - SCANDINAVIA - AIR PHOTOGRAPH MEASUREMENTS

Site Name	Air Photo Scale	Mean	Standard Deviation	Range	Number of Measurements*
	STRIPES (metres)				
Kistrandfjell	1:7,100	5.6	.72	4.7-6.8	5 x 5.4
	1:14,300	4.0	.40	3.5-4.5	5 x 5.2
Kistrandfjell(S of)	1:14,300	6.5	.42	5.9-6.9	5 x 6.4
	1:14,300	7.0	1.15	5.3-8.6	5 x 7.0
Stangvatnet	1:7,050	4.8	.74	4.1-5.9	5 x 8.8
	Unusual Stripes				
Ytre Garadak	1:13,400	6.8	1.09	5.4-8.1	5 x 5.6

* see footnote table D1

N.B. These measurements should be used with caution because the photo scales were small and quality poor. Hence measurements are of marginal accuracy and also only the very largest patterns were measurable.

TABLE D6 RELATION OF PATTERN FORM TO SLOPE — ALASKA

Map No.	Equiforms		Meandroids		Short Elongates		Long Elongates		Stripes		Ice Wedge Polygons		Obvious Solifluction Lobes	
	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
Bendeleben/D5	–	–	$6^\circ15'$	2°	$14^\circ30'$	$3^\circ45'$	9°	$2^\circ15'$	$3^\circ45'$	$3^\circ15'$	11°	$2^\circ50'$	–	–
Bendeleben/C5	Near Zero*		9°	$2^\circ50'$	$6^\circ15'$	$3^\circ30'$	$18^\circ30'$	2°	–	–	7°	$4^\circ5'$	–	–
Bendeleben/C6	1°	Zero*		2°*	$6^\circ15'$	2°	$14^\circ30'$	4°	–	–	9°	$2^\circ50'$	–	–
Bendeleben/B6	–	–	–	–	–	–	11°	$2^\circ50'$	–	–	7°	Zero	–	–
Bendeleben/A6	$1^\circ20'$	Zero*	11°	$2^\circ30'$	$14^\circ30'$	$2^\circ50'$	7°	$1^\circ50'$	$6^\circ15'$	–*	$7^\circ45'$	Near Zero	16°	$7^\circ45'$
Solomon/D6	–	–	9°	$2^\circ15'$	9°	$2^\circ50'$	$14^\circ30'$	$5^\circ15'$	–	–	11°	Near Zero	$14^\circ30'$	Less
Nome/C1	–	–	9°	Near Zero	$6^\circ15'$	$3^\circ15'$	$7^\circ45'$	$1^\circ25'$	–	–	$4^\circ45'$	Near Zero*	$14^\circ30'$	–
Total Range	$1^\circ20'$	Zero*	11°	Near Zero	$14^\circ30'$	2°	$18^\circ30'$	$1^\circ25'$	$6^\circ15'$	$3^\circ15'$*	11°	Zero	16°	$7^\circ45'$

* Very few observations

Note: On all maps the Air Photo coverage was only partial because:-

(a) The photos were of poor quality
(b) Photos were only available for parts of the area.

TABLE D7 RELATION OF PATTERN FORM TO SLOPE - EAST ANGLIA

	Mean	Range	Number of Observations
Equiforms	$0^\circ42'$	$0^\circ24'$-$1^\circ32'$	9
Elongates	$2^\circ36'$	1° -$7^\circ50'$	24
Stripes	$2^\circ50'$	$1^\circ5'$ -$7^\circ10'$	35

APPENDIX E

QUANTITATIVE STUDIES OF PARTICLES

E.1 TECHNIQUES

The quantitative studies of particles involved three main types of measurement:- standard mechanical analysis for particle size; some special studies of the characters of large particles; and a few stone orientation measurements.

The mechanical analysis was by standard techniques except in a few respects. Standard methods of analysis of the very fine portion of a soil sample require oven drying and weighing before measurement of the fractions by differences of settling velocity in suspension. The oven drying may well cause irreversible aggregation of some clays. Hence during the present study samples were only air dried at temperatures not above 25°C and not oven dried at 110°C. The total weight of material passing a +4 ∅ (.063 mm) sieve was obtained by sampling the dispersed soil suspension at 20 cms depth 20 seconds after stirring, at a constant temperature of 26°C. This modification of standard techniques was probably unnecessary for the requirements of the present study. However it is notable that in many cases the clay content of the arctic soil samples is notably higher than might be expected. It may be worthwhile applying similar techniques to samples from other arctic areas.

The East Anglian samples were not given a preliminary treatment to remove organic matter. Specimen tests demonstrated that this treatment was not necessary. Similarly the arctic samples were not given a preliminary treatment to remove carbonates.

Conventional cumulative percentage particle size distribution graphs are supplied with this thesis (figures 83, 84, 86, 87, 90). However simple histograms were found to be much more useful for visual comparison during the analytical work (figures 85, 88, 91).

Analysis of coarse particles in East Anglia (figure 89) was carried out using 25 kg of the original material when stones up to circa 10 cms were present and 50 kg when larger particles were present. The stony sand presented no special problems but the stones in the sand chalk mixture required washing before they could be divided into different lithologies and particle size groups. No attempt was made accurately to measure the particle size distribution of chalk fragments since their friable nature in many cases renders the results of dubious value.

Stone orientation was determined by prismatic compass, abney level and brass or aluminium pointed rod, using the method described by West and Donner (1956).

E.2 MECHANICAL ANALYSIS RESULTS

E.21 Alaska

Figure 83a shows all the particle size distribution curves plotted on one graph. There is a wide variation between samples both in the size of particles present and in their 'sorting' (using the sedimentologist's definition). However almost all the samples have at least 36% particles of silt size or finer. Comparison of figures 83a-d and 84a-d shows that most of the differences between samples from the same site are in the coarse fraction. Only the samples from the earth hummocks at site B2 (see figure 84d) show signs of a major significant difference between the finer fractions of samples at one site (see also Plate 49). Whilst loess is undoubtedly an important element in the mineral soils of the Seward Peninsula (Hopkins 1963), comparison with the loess samples from Central Alaska (see also Pewe 1951) shows that none of the samples from the Seward Peninsula are undisturbed loess, many of the samples showing notably poor sorting. Examination of the histograms (figure 85) indicates even more strikingly the variations of sorting and also shows that the modal particle size varies from site to site.

E.22 East Anglia

The particle size distribution of virtually all samples is bimodal, one mode being in the fine sand size range and the other in the stones. The notable exception is the analyses of the insoluble residue of the chalk which is notably different, the bulk of the particles being clay. This should be remembered when examining analysis results of sand chalk mixture samples, when again chalk has been removed in solution leaving some insoluble residue behind.

There were a number of reasons for suspecting that the sand mode and the stone mode of the samples might not be related. Hence it was desirable to analyse the two modes separately, particularly the sand mode. Careful examination of the histograms (figure 88) indicated that the best point at which to divide the two modes was at $-1.5\ \phi$.

Folk and Inman graphical measures (see Folk and Ward 1957) were calculated for a selection of 16 samples. This gave 12 comparable statistics for each sample. However, the graphical measures did not indicate any systematic significant differences between the three main sites and hence it was not possible to prove similarities or differences between the fine fractions of the sand and sand chalk mixture at any one site. Figure 87d emphasises the similarities between the sand modes at the main sites and the difference from East Anglian Gipping Till and typical arctic samples. The similarity between the sorting of the East Anglian samples and the loess is notable.

E.23 Finnmark

The samples from Finnmark all show notable percentages of silt particles or finer, and in this respect are similar to the samples from the Seward Peninsula. Generally the samples are better sorted than the Alaskan samples, though not as well sorted as the loess. The samples do not suggest sorting of the fine fractions by frost action, though the number of samples is not adequate to exclude this possibility.

E.3 COARSE PARTICLE ANALYSIS

Analysis of the coarse particles from two of the main sites in East Anglia shows clear differences between sites and clear similarities between the coarse particles in the sand and the sand chalk mixture at each site (see figure 89).

E.4 STONE ORIENTATION

The stone orientation diagrams (figure 92) need little explanation. The till diagram (92a) at Garboldisham suggests a movement consistent with that found by West and Donner (1956) for the Lowestoft Glaciation, Stage I, in this area (see also section B.44 for more site details).

Figure 92b shows the orientation of stones in the front of a step or solifluction lobe like feature. The very definite orientation of the stones strongly suggests orientation by frost heave and clearly not by solifluction.

Figure 92c shows a stone orientation from the excavation across the unusual type of large patterns at Ytre Garadak. The similarity to figures 92d-f, which are all from undoubted raised beaches, suggests that this material may be largely undisturbed beach material. However the stone orientation produced by other factors on slopes may give a similar pattern and more work will be needed before this can be proved.

ALASKA MECHANICAL ANALYSIS RESULTS

TABLE E 1a SEWARD PENINSULA

% by weight in each particle size class.

SAMPLE	B1/1	B2/1	B2/2	C2/2	C2/4	C2/B3
DESCR	mineral soil large pattern	earth hummock core	earth hummock subsoil	grey brown mineral soil	very dark grey mineral soil	grey brown mineral soil
-4 ø	0	0	0	0	0	0
-3 ø	0	0	4.02	0	0	2.58
-2 ø	2.15	0	10.20	.47	.73	1.85
-1 ø	2.17	.17	5.69	2.08	2.31	1.38
0 ø	3.81	.06	8.67	1.85	2.44	1.88
+1 ø	8.52	.02	14.79	3.59	4.52	2.57
+2 ø	12.80	.05	16.07	9.02	10.46	8.13
+3 ø	10.89	2.64	9.60	15.53	13.87	16.56
+4 ø	8.64	16.67	9.77	10.31	10.61	11.92
+5 ø	7.44	19.59	8.57	10.06	10.08	8.95
+6 ø	8.57	31.05	5.52	11.20	11.81	8.84
+7 ø	11.43	18.23	2.84	11.30	11.14	10.14
+8 ø	8.09	6.36	1.74	8.82	8.99	8.91
+9 ø	5.32	1.54	.94	5.78	5.83	6.30
>+9 ø	10.16	3.64	1.60	9.99	7.22	10.00
For more detail see	App A.9	Plate 49	Plate 49	Fig 5	Fig 5	Fig 5

Alaska Mechanical Analysis Results continued

TABLE E 1b SEWARD PENINSULA continued

% by weight in each particle size class.

SAMPLE	D5/4	D5/5	D5/7	F2/11	X4/3	X4/6
DESCR	'stone free silt' grey	'stone free silt' mottled	'very stony silt'	'stone free silt'	'silt with scattered large stones'	'silt with only small stones'
-5 ∅	0	0	23.46	0	0	0
-4 ∅	0	0	37.25	0	3.33	0
-3 ∅	0	2.82	4.98	11.19	4.55	2.56
-2 ∅	2.44	3.88	3.32	2.37	5.54	2.00
-1 ∅	1.97	3.73	2.85	2.60	6.12	4.28
0 ∅	1.60	2.41	2.06	2.16	6.43	8.15
+1 ∅	3.10	3.51	1.57	2.51	7.83	8.91
+2 ∅	4.73	4.61	1.80	4.48	9.34	10.24
+3 ∅	5.28	4.63	2.08	4.83	8.49	9.68
+4 ∅	6.10	4.91	2.32	5.43	7.69	9.02
+5 ∅	12.77	12.33	4.70	28.18	6.65	9.15
+6 ∅	17.55	17.46	4.28	10.60	7.63	8.51
+7 ∅	13.78	13.15	3.32	10.12	6.97	7.81
+8 ∅	10.64	10.38	2.40	6.02	5.98	6.79
+9 ∅	6.23	5.95	.96	3.40	4.01	3.90
>+9 ∅	13.80	10.23	2.66	6.10	9.42	8.96
For more details see	Fig 7b	Fig 7b	Fig 7b	Fig 8	Fig 11	Fig 11

Alaska Mechanical Analysis Results, continued

TABLE E 1c SEWARD PENINSULA continued(1) and CENTRAL ALASKA(4)

% by weight in each particle size class.

SAMPLE	A5/1	YAR	ESA	H1	T1
DESCR	frost scar with miniature patterns	loess (Central Alaska)	loess (Central Alaska)	large pattern (Denali Highway C.Alaska)	large pattern (Central Alaska)
-5 ∅	0	0	0	0	0
-4 ∅	0	0	0	0	15.65
-3 ∅	10.34	0	0	2.09	7.23
-2 ∅	10.89	0	0	5.81	5.76
-1 ∅	8.60	0	0	5.23	5.46
0 ∅	7.06	.02	0	6.36	5.21
+1 ∅	6.41	.01	.02	7.10	3.98
+2 ∅	6.16	.12	.11	8.99	3.02
+3 ∅	5.58	3.60	.73	9.28	1.98
+4 ∅	6.18	30.02	16.06	9.42	2.50
+5 ∅	6.52	43.39	57.58	13.33	11.50
+6 ∅	8.25	13.90	18.62	11.24	12.37
+7 ∅	8.32	3.50	3.26	8.65	8.57
+8 ∅	5.72	1.60	1.30	6.06	5.90
+9 ∅	3.46	1.14	.62	3.36	3.75
>+9 ∅	6.51	2.71	1.69	3.06	7.12
For more detail see	plate 3	E.21	E.21	section 4.2.8	section 4.2.11

EAST ANGLIAN MECHANICAL ANALYSIS RESULTS

TABLE E2a1 GRIMES GRAVES PATTERN SITE

% by weight in each particle size class(omitting calcareous fraction)

SAMPLE	GA3	GA5	GA6	GA7	GA8
DESCR.	sand chalk mix, very chalky	in situ chalk	sand trough flinty	sand chalk mix, very sandy	sand with many flints
-5.75 ø	0	0	0	0	**
-5.5 ø	0	0	19.04	0	-
-5.25 ø	0	0	6.23	0	-
-5.0 ø	0	0	12.81	0	-
-4.75 ø	0	0	3.27	0	-
-4.5 ø	0	0	5.31	2.29	-
-4.25 ø	0	0	4.38	3.65	-
-4.0 ø	0	0	3.04	7.15	-
-3.5 ø	7.32	0	3.11	8.17	-
-3.0 ø	0	0	1.18	8.89	-
-2.5 ø	.16	0	.38	9.43	-
-2.0 ø	.11	0	.32	9.73	-
-1.5 ø	.09	0	.25	10.19	41.08***
-1.0 ø	.09	0	.37	.33	.88
-0.5 ø	*	*	*	*	*
0 ø	1.58	0	2.17	2.79	4.90
+0.5 ø	1.39	0	1.25	2.57	2.32
+1.0 ø	2.14	0	1.46	2.66	2.67
+1.5 ø	6.34	0	2.96	6.15	4.74
+2.0 ø	17.74	0	7.50	14.95	9.18
+2.5 ø	18.62	0	6.07	16.18	9.17
+3.0 ø	15.70	0	7.01	14.48	9.41
+3.5 ø	11.62	0	5.79	12.12	8.25
+4.0 ø	8.41	.97	2.99	9.48	3.52
+5.0 ø	3.41	2.90	1.23	3.64	3.87
+6.0 ø	.92	4.83	.54	1.22	**
+7.0 ø	.56	5.80	.37	.46	-
+8.0 ø	.26	10.63	.18	.19	-
+9.0 ø	.42	2.90	.14	.28	-
>+9.0 ø	3.12	71.98	.62	2.31	-
% Calcareous in original sample	78.32	98.34	0	30.68	0

* This Fraction is included with the 0 ø fraction.

** Only the sand fractions of this sample were analysed in detail.

*** -1.5 ø AND all material coarser.

East Anglian Mechanical Analysis Results continued

TABLE E 2a2 GRIMES GRAVES PATTERN SITE continued(3) and HIGH LODGE(1) % by weight in each particle size class (omitting calcareous fraction).

SAMPLE	GA 10	GB1	GB3	HA1
DESCR	sand with few flints	sand trough	sand chalk mix	proven Gipping Till
-5.75 ø	0	2.20	0	0
-5.5 ø	0	4.78	0	0
-5.25 ø	0	5.10	.52	0
-5.0 ø	0	5.03	.27	0
-4.75 ø	0	6.14	.73	0
-4.5 ø	1.85	6.02	1.72	0
-4.25 ø	.49	5.05	1.11	0
-4.0 ø	0	5.77	1.39	3.50
-3.5 ø	.69	4.26	1.66	0
-3.0 ø	.37	1.62	1.10	.74
-2.5 ø	.18	.33	.22	.59
-2.0 ø	.13	.20	.23	.53
-1.5 ø	.17	.24	.36	.46
-1.0 ø	.22	.55	.39	.15
-0.5 ø	*	1.80	*	.30
0 ø	1.89	1.34	3.63	.40
+0.5 ø	1.67	1.63	2.27	.70
+1.0 ø	2.80	2.21	2.92	1.64
+1.5 ø	8.06	5.67	6.81	3.83
+2.0 ø	20.95	10.82	17.89	5.77
+2.5 ø	21.42	8.93	15.96	5.38
+3.0 ø	18.76	8.68	14.82	5.22
+3.5 ø	12.45	6.96	11.47	3.98
+4.0 ø	5.18	3.22	7.16	3.15
+5.0 ø	.85	5.82	3.49	6.61
+6.0 ø	.12	.17	.96	6.21
+7.0 ø	.20	.09	.49	5.16
+8.0 ø	.23	.06	.27	5.42
+9.0 ø	.15	.06	.29	4.55
>+9.0 ø	1.17	.50	1.86	35.72
% Calcareous in original sample	0	0	22.78	62.76

* This fraction is included with the 0 ø fraction.

East Anglian Mechanical Analysis Results continued

TABLE E 2b KNETTISHALL HEATH

% by weight in each particle size class(omitting calcareous fraction)

SAMPLE	KA1	KA4	KA6	KA9	KB1	KB3
DESCR	in situ chalk	sand chalk mix, very sandy	sand trough	chalk rich pseudopod	sand trough	sand chalk mix
-6.0 ϕ	0	0	0	**	.90	0
-5.75 ϕ	0	0	0	-	1.17	0
-5.5 ϕ	0	0	0	-	.58	.36
-5.25 ϕ	0	0	0	-	1.40	.31
-5.0 ϕ	0	0	0	-	2.15	0
-4.75 ϕ	0	0	4.25	-	2.42	.34
-4.5 ϕ	0	0	.97	-	1.98	.52
-4.25 ϕ	0	0	2.27	-	2.45	.59
-4.0 ϕ	0	5.00	2.56	-	2.97	1.44
-3.5 ϕ	0	1.40	2.55	-	4.22	2.14
-3.0 ϕ	0	1.40	1.43	-	3.21	1.85
-2.5 ϕ	0	1.58	1.13	-	2.09	1.20
-2.0 ϕ	0	.88	.78	-	1.29	.75
-1.5 ϕ	0	1.15	.58	-	.88	.57
-1.0 ϕ	0	.79	.31	.37	.68	.78
-0.5 ϕ	*	*	*	*	*	*
0 ϕ	0	1.39	.62	1.26	1.81	1.31
+0.5 ϕ	0	1.40	.32	1.54	.88	1.06
+1.0 ϕ	0	3.22	1.10	3.07	1.57	2.25
+1.5 ϕ	0	9.29	5.19	9.82	4.77	6.99
+2.0 ϕ	0	19.01	18.66	26.96	14.62	16.96
+2.5 ϕ	0	17.90	22.75	25.23	17.23	17.95
+3.0 ϕ	0	13.18	17.06	18.75	13.42	13.35
+3.5 ϕ	0	7.55	9.84	8.84	7.70	8.21
+4.0 ϕ	14.98	4.06	5.17	4.16	4.40	4.68
+5.0 ϕ	2.38	4.13	1.75	**	2.68	4.07
+6.0 ϕ	0	1.84	.19	-	.46	2.40
+7.0 ϕ	1.78	1.14	0	-	.77	1.33
+8.0 ϕ	2.38	.46	.09	-	.19	.75
+9.0 ϕ	17.84	.30	.02	-	.17	.48
>+9.0 ϕ	60.64	2.75	.38	-	.96	7.34
% Calcareous in original sample	99.33	24.32	0	94.39	0	29.82

* This fraction is included with the 0 ϕ fraction.

** Only the sand fractions of this sample were analysed.

East Anglian Mechanical Analysis Results continued

TABLE E2c THE DROVE, BRETTENHAM

% by weight in each particle size class(omitting calcareous fraction).

SAMPLE	DA1	DA2	DA3	DA5	DA6
DESCR.	sand trough	sand chalk mix, very sandy	in situ chalk	'clay shift'	sand chalk mix, medium
-6.0 ø	0	0	0	0	0
-5.75 ø	0	13.47	0	0	0
-5.5 ø	0	0	0	0	0
-5.25 ø	0	0	0	0	0
-5.0 ø	0	0	0	0	0
-4.75 ø	0	3.56	0	0	0
-4.5 ø	1.04	0	0	0	.78
-4.25 ø	.52	.55	0	0	0
-4.0 ø	.29	1.16	0	0	3.10
-3.5 ø	.09	1.58	0	0	.45
-3.0 ø	.16	.45	0	0	.24
-2.5 ø	.12	.30	0	0	.30
-2.0 ø	.10	.11	0	.28	.17
-1.5 ø	.08	.14	0	.48	.25
-1.0 ø	.10	.20	0	.18	.18
0 ø	.48	.43	0	.58	.39
+0.5 ø	.86	.61	0	.90	.67
+1.0 ø	2.39	1.77	0	2.02	1.93
+1.5 ø	10.12	6.69	0	6.57	7.11
+2.0 ø	30.14	17.64	0	19.85	18.58
+2.5 ø	25.04	17.71	0	19.25	19.70
+3.0 ø	14.22	13.55	0	15.24	16.65
+3.5 ø	6.54	7.92	0	10.15	11.51
+4.0 ø	3.29	4.68	.46	6.54	6.40
+5.0 ø	1.73	3.99	0	3.40	4.69
+6.0 ø	1.03	.74	0	1.45	1.75
+7.0 ø	.39	.73	3.83	.78	.91
+8.0 ø	.32	.41	1.53	.76	.47
+9.0 ø	.07	.12	3.06	1.14	.32
>+9.0 ø	.88	1.61	91.12	10.44	3.47
% Calcareous in original sample					
	0	12.94	99.54	0	34.05

SCANDINAVIAN MECHANICAL ANALYSIS RESULTS

TABLE E3a

% by weight in each particle size class.

SAMPLE	07A/3	U4A/1	U5A/1	U5A/2	U5D/4	U5D/8
DESCR	brown silt	olive mineral soil	grey mineral soil	light brown mineral soil	grey 'low fines'	grey 'high fines'
-5 ø	0	0	0	0	0	0
-4 ø	0	0	0	0	1.36	0
-3 ø	0	0	0	.84	4.21	4.40
-2 ø	0	11.84	.93	1.83	4.24	3.54
-1 ø	.11	6.37	3.46	2.21	4.12	2.80
0 ø	.46	3.68	5.27	3.39	4.17	2.52
+1 ø	2.04	3.52	6.75	4.88	5.14	2.88
+2 ø	4.85	5.02	10.48	9.96	4.79	5.72
+3 ø	10.58	7.99	13.44	15.64	12.65	8.74
+4 ø	11.35	13.27	14.78	20.38	15.67	11.52
+5 ø	33.01	17.38	17.15	14.72	18.57	20.80
+6 ø	15.42	12.65	10.69	11.60	11.15	15.48
+7 ø	9.94	7.67	6.01	5.41	6.09	9.32
+8 ø	5.93	4.20	3.98	3.07	3.68	6.35
+9 ø	2.96	2.58	3.17	1.83	2.26	3.58
>+9 ø	3.36	3.85	3.89	4.24	1.91	2.34
For more detail see	plate 140	fig 70	fig 55	fig 55	fig 53	fig 53

Scandinavian Mechanical Analysis Results continued

TABLE E 3b

% by weight in each particle size class.

SAMPLE	V3D/1A	V3D/1B	V3D/2A	V4B/1	W1B/1	W1B/2
DESCR	grey mineral soil	grey-brown mineral soil	grey mineral soil	fines amongst large stones	grey mineral soil	brown mineral soil
-5 ∅	0	0	0	0	0	9.12
-4 ∅	18.33	0	0	0	27.70	7.62
-3 ∅	3.30	6.37	0	0	3.85	11.33
-2 ∅	7.80	12.17	18.79	13.72	3.83	6.12
-1 ∅	3.76	7.99	7.87	4.61	2.53	1.39
0 ∅	4.65	6.92	4.20	4.38	1.97	1.16
+1 ∅	3.55	4.89	3.30	12.02	1.93	1.80
+2 ∅	3.80	4.95	4.90	22.15	2.16	2.72
+3 ∅	6.83	9.08	11.32	17.09	6.48	6.58
+4 ∅	12.66	15.22	18.41	10.92	13.23	13.49
+5 ∅	12.78	12.68	12.94	6.41	16.17	23.82
+6 ∅	9.12	7.75	7.52	4.63	9.80	8.47
+7 ∅	5.90	4.86	4.37	2.21	3.66	2.48
+8 ∅	3.81	4.06	2.63	.96	2.46	1.29
+9 ∅	1.98	..96	1.70	.49	1.53	.82
>+9 ∅	1.74	2.10	2.05	.41	2.72	1.81
For more details see	fig 59	fig 59	fig 60	fig 71	fig 68	fig 68

APPENDIX F

INTERPRETATION OF PATTERNS FROM AIR PHOTOGRAPHS

F. 1 SEWARD PENINSULA, ALASKA

F. 11 Recognition of Features

F. 111 General Factors Affecting Recognition of Patterned Ground. Patterned ground has very varied expression on aerial photographs. In general more areas of large forms of patterned ground can be distinguished on aerial photographs than can be distinguished on the ground. In the Seward Peninsula there is a variety of textural patterning seen on aerial photographs and it is necessary to distinguish how much of this represents the forms of patterning which are the main subject of study. The interpretation of patterned ground from aerial photographs in this area was hindered by the fact that much of the available air photograph cover is unsuitable for this type of work.

Most of the photographs were taken at far too small a scale for patterns to be clearly distinguished. This is easily appreciated by considering the size that a 5 metre wide stripe pattern would be on photographs of various scales, as shown in Table F.I. With average quality photographs individual patterns of the size being studied cannot be distinguished at scales smaller than 1:12,000 to 1:15,000.

TABLE F.I.

Width of Image of 5 metre wide stripe pattern at various scales

Scale	Width of Image
1:5,000	0.2 mm
1:10,000	0.1 mm
1:20,000	0.05 mm
1:50,000	0.02 mm

On exceptionally good photographs patterning with a strong vegetational contrast may be confidently identified at scales as small as 1:40,000. In general, however, photographs of a scale larger than 1:20,000 are needed to confidently recognise the pattern forms, and larger scales as mentioned above before individual patterns can be seen well enough to allow measurement and observation of detailed form. The only photographs available of the area that were sufficiently large in scale did not show any very good areas of patterning, so that detailed observations on patterned ground form are largely based on field data.

F. 112 Very Large Scale Linear Downslope Features. On many of the air photographs dark lines up to several hundred metres wide are seen running down hill sides. These features are even more striking when viewed from valleys in the field. Broad lines of dark vegetation run downslope on the lower slopes of many hills. These have been described by Hopkins and Sigafoos (1951 pp 58-59). They are simply areas of denser vegetation along drainage lines. They often have a dendritic pattern as can be seen on Plate 17. The vegetation is dominantly willow, though sometimes birch is important. Often small willow thickets are elongate downslope again suggesting lines of differing drainage conditions, though there is little or no visible relief related to these smaller features. Local variations such as depth of active layer and type of soil may have as much effect on drainage lines as minor relief variations.

F. 12 Distribution of the Patterns in the Seward Peninsula

The area of the field work was almost entirely confined to a strip of country a few miles wide either side of the road running north from Nome for about 125 km. Most of the air photograph cover of the Seward Peninsula that was examined was also of this general area. Some mapping was carried out using air photograph runs to the north east of the northernmost part of the area, across the Midnight Mountain area. Additional photographs were examined from the general area of Cape Wooley, to the west of Nome.

F. 121 Limitations of the Maps Produced by Air Photograph Interpretation

All localities shewing well marked patterns on the air photographs proved to have patterns on the ground. However, not all well marked patterns on the ground were distinguishable on the air photographs. For example the patterns seen on Plate 25 were first examined after being identified from the air photographs, whereas the patterns seen on Plate 21 were identified on the ground but were not visible on the air photographs even with very careful examination. It should be remembered that many of the air photographs are of very small scale and very poor quality. All recordings of patterns on the maps probably represent patterns on the ground.

A full description of the possible interpretations of the symbols used in the mapping is given in Section F.13. It must be emphasised that certain patterns with distinct forms on the ground may not be distinguishable on the air photographs. It is important to remember that the pattern symbols used in the mapping represent the type of patterning visible on the air photographs. Not enough data on the variations of pattern forms with relief are available from the area to allow precise correction of the air photograph interpretation. Figure 21 shows two examples of mapping of patterned ground from air photographs.

F. 122 General Topographic Distribution of the Patterning. In the Seward Peninsula equiforms and near equiforms were only found on areas with very slight slope. The maximum slope on which absolutely clear equiforms were seen on the air photographs was about 1½ degrees, and probably most are on slopes somewhat less than these. It was very noticeable that equiforms were only present on raised flat or very

gently sloping areas. They are not present on any of the numerous and extensive flat or near flat areas that are in topographically low positions. There is a strong suggestion that equiforms of the type being studied are best developed on ridge rather than plateau situations. Ice wedge polygons are marked most clearly on air photographs on flat areas in topographically low positions such as the Kuzitrin Flats. Elongate and stripe forms are far more common than equiforms and are generally much better marked. An attempt was made to analyse the results of the air photograph mapping in order to define the range of slopes on which the various pattern forms develop. The results were mainly negative. Table D6 shows the results of this analysis.
The table shews clearly that equiforms are only found on slight slopes. The table does not shew a distinctive range of slope angles for meandroids, elongates or stripe forms. There are not enough clear examples of the latter to expect any conclusion. In general it is thought that this absence of clear correlation between slope and pattern form is due to the lack of precision in the interpreting and recording of the patterns from the air photographs rather than a real absence of correlation of the features on the ground with slope. The main conclusion to be drawn from Table D6 is that it confirms that the symbols on the maps recording the air photograph observations should be taken as an indication of the pattern forms distinguishable on the air photographs rather than a true and complete map of the pattern types on the ground.

It is interesting to note from table D6 that ice wedge polygons occur in the area on slopes up to about 10 or 11 degrees. Well marked large solifluction lobes only occur in association with quite steep slopes (14 to 16 degrees), though some are found on footslopes below steep slopes where the slope may be nearer 7 or 8 degrees.

F. 123 Regional Distribution of the Patterns. It is not possible to precisely describe the regional distribution of the patterns of the area from the aerial photograph mapping because of the difficulties of the variability of available air photograph cover and the consequent difficulties of aerial photograph interpretation. The density of patterned ground frequently appears to vary more with quality of air photograph print than with natural variable.

Nome Coastal Area. Patterns were restricted in distribution in the general area of the Nome Coastal Plain. On the Coastal Plain proper definite patterns of the 5 to 7 metre size only occurred on limited areas with locally steeper slopes, i.e. at least 2½ degree. It is of interest to note that a significant number of patterned sites to the north and east of Nome occur over the top of deposits mapped by Hopkins et al (1960) as till and outwash of Nome River Glaciation and also, judging from their section, the patterns are developed in peat, loess and colluvium of Wisconsin to recent age which overlies the glacial deposits.

Near Cape Nome an isolated ground study was made of clear elongate or stripe forms. These occur where Hopkins et al (1960) mapped deposits of the Second Beach and also "Estuarine Sandy Silt behind Second Beach Shoreline." It is difficult to be certain from their map which of these two underlie the site, but the patterns probably overlie the latter deposits. The bench form of the local topography at this site would accord with a raised beach interpretation. This Second Beach and its associated deposits are thought by Hopkins et al to be of Sangamon age.

On the footslopes of the hills flanking the Nome Coastal plain patterns are quite common between 30 and 150 metres, but rather sporadically distributed above this height.

Nome River Valley. The air photographs that were available for the Nome River Valley and adjacent hills were particularly poor in quality. On the hills flanking the valley a scatter of patterns were distinguished on the air photographs whenever the photographs were sufficiently good. None were detected flanking the northern half of the valley because of the lack of suitable air photographs. Ground observations were largely confined to the area immediately adjacent to the river and the lower parts of the valley sides. Patterns were not commonly well marked. A number of sites were seen with well marked small ridges of 'solifluction lobe' form, which were very similar to those described from sites C3 and C5. Careful ground observation suggested that the number and ease of distinguishing pattern sites decreased in the valley from north to south.

Salmon Lake Area and the Grand Central Valley. There are patterns on the lower slopes of the hills to the north of Salmon Lake. In some cases patterns were seen on the air photographs to be developed on the terraces of large solifluction lobes. Site B1 is located on lower lying ground which must have been overridden by the glacial ice that deposited the Salmon Lake Terminal moraine. A particularly careful study was made of the air photographs of the Grand Central valley in order to attempt to see if patterns could be related to retreat stages of the Salmon Lake Glaciation. No clear stages could in fact be distinguished from the air photographs. Only poorly marked patterns were seen in the valley, about one third of the distance from Salmon Lake to the head of the broad section of the valley. Clear ice wedge patterns were seen on deltas and colluvium farther up the valley.

The general conclusion from the Salmon Lake and Grand Central Valley areas is that patterns are developed on areas that were covered by ice during the Salmon Lake Glaciation, but it is not possible to be any more specific with the information available.

Middle Kruzgamepa Valley Area. Patterns were found throughout this area whenever close examination was made except on the very flat areas adjacent to the river and on slopes steeper than 15 to 20 degrees. The absence of patterns in the latter case is because these slopes are dominantly bare rock or rock waste. At site X4 patterns were found overlying glacial deposits of probable Nome River age. Patterns are also extensive in the area of Iron Creek.

The Kuzitrin and Kruzgamepa Confluence Area. No patterns of the type being studied were seen on the flat low lying areas, though ice wedge polygons were abundant. Ground investigation revealed the presence of poorly marked equiforms on flats above small bluffs marking low terraces of the Kruzgamepa River. On upstanding hills, such as Labaree hill and Bunker Hill, well marked patterns are common.

Kuzitrin Flats Area. The absence of patterns of the type being studied, on this type of area, has already been mentioned above. Ice wedge polygons are abundant and the area is notable for the numbers and sizes of the pingos present.

The Coffee Dome/Quartz Creek Area. The aerial photographs of this area were particularly poor in quality and only exceptionally well marked patterns could be distinguished. Ground observations proved patterns present on suitable sites throughout this area.

Midnight Mountain Area. The air photograph runs across this area were of larger scale than those of most of the other areas referred to above. These photographs shewed widespread, well marked patterns are present in this area. The patterns were sufficiently well marked to allow clear distinction of individual patterns and clear examination of the relationship of patterns with topographic forms. Ground investigation in this area was confined to a short distance between the Kougarok road bridge and Neva Creek. Patterns were widespread and easily distinguished in this section, suggesting that the patterns may in fact be more widespread in this area. However it should also be borne in mind that the relief in this area is favourable for getting good perspective view of the patterns, which greatly aids ground identification of the patterns.

Other Localities in the Seward Peninsula. Patterns of the type that are the main subject of this study were also observed on air photographs of the Cape Wooley area, between the Sinuk and Tisuk Rivers.

Hopkins and Sigafoos (1951) report similar features to be extensive in the Imuruk Lake area (east of the Midnight Mountain area, and some 160 km north east of Name). Hopkins, Karlstrom et al (1955) publish a photograph of the area of Noxapaga River shewing elongates overlying ice wedge polygons. Hopkins (personal communication) also reports similar patterns to be present throughout the Seward Peninsula.

Summary

The patterns being studied seem to be present in all areas of the Seward Peninsula that have been examined. The writer has a subjective impression that patterns are found more frequently and better marked in the centre of the Seward Peninsula than nearer the South Coast. However, neither the data available from this study, nor the previous work by Hopkins and others, allows quantitative estimates to be made of relative density of the pattern distribution.

F. 13 NOTES ON THE AERIAL PHOTOGRAPH SYMBOLS USED IN THE AERIAL PHOTOGRAPH MAPPING OF AREAS OF THE SEWARD PENINSULA, ALASKA.

All the symbols described in this section are shewn on figure 21.

In the first instance a system was adopted using dots for equiforms, pecked lines for elongates and continuous lines for stripes. Both the latter were marked in the direction of the features being recorded, and an arrow added pointing downslope. In practice a symbol for the 'meandroid' category of patterning seen on air photographs was found to be essential and the symbol 'c' was used (details of the 'meandroid' pattern form are described in Section F.23). This category includes patterns intermediate between clear equiforms and clear elongates; poorly marked elongates and also occasionally poorly marked stripes. Whilst in some ways it is unsatisfactory to include all these variations of the patterns together it should be remembered that equiforms are in general much less well marked than stripes. In practice therefore poorly marked elongates, and intermediate equiform/elongate forms are indistinguishable in the majority of cases.

Thus the absolutely full interpretation of the symbols used in the initial mapping and also in figure 21 is as follows:

Dots - clear equiforms (rare).

Pecked lines with arrows - elongates with long axes at least 4 to 10 times the width of the patterns; plus some stripes that are not clearly marked but are definitely patterns showing some elongation and which cannot be distinguished from elongates on the photographs.

Continuous lines with arrows - clear stripes (rare).

'c' Symbol - 'meandroids'. This description covers a range of similar markings on the photographs which are found from ground observations to represent a variety of features including patterns intermediate between equiforms and elongates; poorly marked equiforms, elongates or stripes (the indistinct marking may be due to ground or photographic conditions); any of the previously mentioned patterns overlying ice wedge polygons; very occasionally this symbol may have been used for markings that represented ice wedge polygons only.

'c' Symbol combined with pecked lines - represents short elongates (length less than 6 to 10 times the width); poorly marked 'long' elongates and stripes; or poorly marked elongates and stripes overlying ice wedges. This symbol always represents definite examples of the patterns of the type being studied, and does not include any known examples of ice wedge polygons alone.

'W' symbol - Ice wedge polygons. When combined with any of the above symbols represents definite ice wedge polygons underlying other types of pattern.

In summary dots and continuous lines represent clear patterns. Pecked lines with or without 'c' symbols represent definite patterns of the type being studied, but with varying clarity. The 'c' symbol includes a range of similar markings that include a few phenomena that are not patterns of the type being studied.

F. 2 EAST ANGLIA

This study is not the first to use air photographs to detect areas of patterned ground in East Anglia.

Perrin (1963) reported on the use of air photographs in mapping the patterns of the Breckland area. He noted that the patterns are particularly easily recognised on air photographs. He mapped some 150 occurrences in different parts of Breckland. Perrin suggested that the patterns could be mapped and related to slope and aspect from air photographs. He further suggested that the nature and depth of soil in association with the patterns could be deduced from the photographs if the observer was particularly familiar with the area. Perrin reported that the patterns are best seen at certain seasons of the year - patterns in the soil from February to April and vegetation and crop patterns from March to July. He also noted that patterns at any one locality do not always show on every cover of air photographs.

Williams (1964) produced a map of patterned ground of Britain, largely from air photographs (see figure 41). The distribution of patterns in East Anglia as shown by him is essentially similar to the one shown on the maps accompanying this thesis, though many more localities were mapped during the course of the present study.

A major part of the time devoted to the present study was spent in producing a map of the patterns of East Anglia from air photographs. All previous maps of patterned ground were disregarded (the only important one being the one produced by Williams 1964). Specimens of the result can be seen in figures 43, 44, 45, 46, and 47. The mapping of patterns by air photograph interpretation suffered due to the fact that it was one of the earliest parts of the present study. Ground checks were carried out at the time of the air photograph work and the result is, within limits, reliable. However, there is little doubt that after the experience gained later in the study, particularly work in the

Arctic, a more precise map could have been produced.

F. 21 Methodology

The method used was very simple. As far as possible complete air photograph covers were used. Any occurrences were marked on a map and a record made of the air photograph number, date and general location of the patterns. Special features were also recorded. These records and index are available for future workers. Stereoscopic viewing proved too slow for the mapping, in view of the enormous numbers of photographs involved, and also because of the very high power of magnification needed to identify many of the patterns. Virtually all the mapping was carried out with a high power magnifying glass with a very wide field of view. Only areas of particular interest were examined stereoscopically. A total of 10,000 air photographs were examined and some 3,500 recordings of patterns made (though some of these are duplicating the same patterns).

F. 22 Air Photographs Used in the Study

The mapping was originally carried out on 1:25,000 maps. Since the total area covered was far too large to see as a whole at this scale these observations were transferred to 1:63,360 outline maps. Copies of these maps are in the pocket at the back of this thesis (maps 8-12). For other purposes the patterns have been replotted at 1:500,000 and 1:1,000,000 (see figures 39a and 40).

Three main sources of air photographs were used :-

1. R.A.F. vertical photography taken between 1946 and 1951. The quality of this photography was extremely variable and is generally of rather poor quality (see Plates 92 and 107).
2. Oblique photography by the Department of Aerial Photography, University of Cambridge. From 1946 onwards Dr. St. Joseph and associates of this department have photographed archaeological sites, geomorphic features, vegetation etc. for academic and educational purposes. These photographs are of excellent quality but there has never been any intention of making this an overall coverage. (See Plates 77, 87, 93 etc.)
3. Commercial Vertical Air photography by BKS Surveys, taken circa 1962. This photography is of excellent quality for the County of Cambridge only, but unfortunately was taken at harvest time so that much of the ground is heavily obscured by cultivation marks (see Plate 106).

The quality and number of photo runs examined for any one area is variable. To check on the accuracy of coverage a map of all the observations from vertical air cover was plotted and then a separate one for the sporadic, but high quality cover from the Department of Aerial Photography Cambridge (figure 40). The fact that very few fresh areas of patterns were located on the latter cover suggests that the general reliability of the map is good, though undoubtedly this map does not by any means shew every occurrence of patterned ground.

F. 23 Classification used for Mapping

The classification of surface patterns used in this thesis is: equiforms, elongates, stripes, steps, irregular 'patterns'. On the maps produced from air photographs only the type of patterns investigated in detail are marked. The classification used is:- equiforms, elongates, stripes, meandroids without marked elongation and meandroids with marked elongation. The symbols used can be seen in figure 42.

Elongates are patterns shewing a regular form and marked downslope elongation. The definition of this category was on appearance, and measurements of the patterns placed in this category proved to have length:width ratios of 2:1 to 7:1. The symbol used gave some idea of the amount of elongation. Thus the lower limit of stripes was approximately length:width ratio 7:1.

The meandroid category regrettably includes three different sorts of observation. This category was introduced to cover all pattern observations that were difficult to classify. Firstly it includes patterns intermediate between equiforms and medium elongates - simply because at the beginning of the study no worker had proposed a class for these patterns, which could clearly be called neither 'polygons' nor stripes. The class 'elongates' proposed by the present writer obviates this difficulty for future workers. Secondly the term meandroid includes forms of patterns which are characteristic on air photographs but which are not valid on the ground. This is because the air photographs, or the feature marking the pattern, is only recording part of the pattern form. This was not really appreciated until after two summers of field work in the Arctic. Figure 56 illustrates this point. Thirdly the category meandroids includes patterns which are not sufficiently clearly marked to classify, but which are definitely patterns. In hindsight it would have been better if these three categories of meandroid had been marked separately, rather than all by the same symbol.

F. 24 Problems of Recognition of Patterns

The main difficulty arises due to the surprising number of accidental features that can look like patterned ground. The commonest is the cultivation pattern. It may be impossible positively to identify straight stripes without actually digging sections in some cases. Even degraded stock feeding and fertiliser heaps can be mistaken for equiforms. Many vegetation colonisation patterns, particularly in bog and fen communities, can strongly resemble patterned ground.

APPENDIX G
FIELD TECHNIQUES AND PROBLEMS

G.1 GENERAL

Most of the field work was simple observation and recording. Generally only very simple techniques were used because of the large number of sites to be recorded. Undoubtedly the most important instrument used during the field work was the camera. Much of the recording was of simple visual evidence which was extremely difficult to record entirely objectively. Thus the photographic record is extremely valuable, especially where ideas and interpretation have changed markedly. The camera is also very efficient when considered in relation to the high cost of field work time. A very large number of plates are presented in this thesis firstly to save many words, secondly to present a range of the visual evidence in as objective a form as possible and thirdly because photographs are infinitely better than lengthy written descriptions for use by future workers. Despite the large amounts of photographic materials and processing during the present study the cost was only circa 2% of the total costs.

A very difficult part of the field work was the selection of 'ideal' or 'typical' patterns for excavation. Since the excavations can be only a very small sample the selection of sites is a very difficult problem, especially since every individual pattern tends to have some surface variation and since sections through many patterns demonstrate considerable variation from pattern to pattern. The only solution to this problem is more experience and a larger sample.

The excavation of sections across large patterns requires very large pits to allow study of all the structures. In East Anglia excavation of 60 cubic yards of material or more was needed. The only practical method was by hired mechanical excavator, which proved reasonably economic (circa 10 to 15 shillings per cubic yard including excavation and infilling).

In the Seward Peninsula and in Finnmark hand excavation and blasting were used. For the first excavation in Alaska some 5 tons of material were removed by blasting (see Plate 60) and then a further 15 tons were removed by hand excavation of material thawed by exposure, giving the result seen in Plate 9. Even on slopes drainage was a severe problem and during the course of this excavation a longitudinal section was excavated not by choice but simply because it was essential for drainage (see figure 5). Unless such extensive drainage is undertaken the wet silt sections will only stand for a short period before collapsing - a few days at most - and flooding is often much more rapid. Other pits were excavated mainly by explosives alone with only a little hand trimming. In Finnmark similar methods were used.

In Alaska a SIPRE ice auger (Hughes and Terasmae 1963) was used for coring frozen material (see Plates 57-59). A simple adaption to a post hole attachment on a chain saw motor allowed very rapid boring. This worked easily in permanently frozen silt, even when a few stones were present (mica schist). Care must be taken to prevent the auger becoming frozen in. Addition of meltwater and coring in short lengths proved a workable solution to this problem. If meltwater is used care must be taken to remove contaminated material if pollen analysis etc. is contemplated. The ice auger will not work if as little as 10 cms of thawed wet silty mineral soil is present over the permafrost.

Sections were drawn by suspending crude plumb lines at metre intervals, suspending a tape between a pair of metre plumb lines and then sketching the section on graph paper at a scale varying around 1:20.

The techniques used in the air photo studies and sample analysis are described in separate appendices.

The costs and logistical problems of work in sub-arctic regions should not be underestimated. Cederstrom (1953) reporting on the problems of boring a test well at Kotzebue reports the problems in order of their difficulty as :-

1. Logistical,
2. Lack of, and excessively high cost of, technical services and materials,
3. Personnel,
4. Permafrost.

Sellman and Brown (1965 p 7) report the cost of three months' field work for two qualified geologists drilling near Point Barrow in terms of cost per metre of drill core recovered. The cost was "$115/metre ($35/ft) based on recovery of approximately 200 metres of core. This value agrees favourably with Fairbanks."

Costs in the Seward Peninsula during the present study were minimised by restriction of the field programme, particularly restricting mobility, and more especially by the generosity of the local inhabitants and of U.S. scientists and government agencies. Cost per hour of field work was around £5-£6 per hour (though but for generosity this should have been £7-£8 per hour). This compares with estimated costs of £2.5 to £3.5 per field work hour in Finnmark and £1.5 to £2 per hour in East Anglia (N.B. In U.K. many of the 'hidden costs' such as equipment, time spent in direct preparation and travel, remuneration of worker(s) etc. are often not reckoned).

G.2 THE USE OF EXPLOSIVES FOR GEOMORPHOLOGICAL WORK

Since the use of explosives by British geomorphologists has been rather limited a few notes on the experience gained during the present study may be useful. These notes are <u>not</u> intended to cover the general technical and safety aspects of handling explosives and such information must be obtained from suitable authorities. During the present study the aim was to produce clean, undisturbed sections several metres long in a minimum of time.

If a small charge is used in soil it will tend to produce only a chamber. The charge will attempt to lift more material than it is capable of blowing clear, and will rupture the intended section face, possibly also causing extra material to be forced into the ruptures (see Plate 44). A more generous charge will blast all the material clear of the section, leaving clean faces to the crater which will only be disturbed for a few cms. The size of charge needed to achieve this effect will vary with the nature of the ground and can only be determined by trial and error on the site. The main point to be remembered is that undercharging can completely ruin a section whereas overcharging will only be somewhat wasteful of explosive (though overcharging will lead to more flyrock for a greater distance, and therefore safety precautions need careful attention). The present writer found that blasting a hole by 50 to 60 cm stages was the most efficient. Commonly this needed $\frac{1}{2}$ lb charges at 50 cms or $\frac{3}{4}$ lb charges at 60 cms depth, with the charges spaced 1.5 to 2.5 m apart. This gives an excavation some 1.5 to 2.5 m wide.

There is a tendency for the blast to rip back the turf or sod where a continuous sheet of vegetation is present at the surface. This is easily prevented by making a single spade cut through the vegetation and roots around the limits of the planned excavation (e.g. in Plate 61 this was the only hand work in the production of the pit seen).

When individual charges are initiated at different times by powder burning fuse this often does not blow all the material clear (see Plate 60). Instantaneous initiation is more effective and produces a much neater and therefore more easily used section (see Plate 61 and 64). This can be achieved by use of detonating fuse (e.g. I.C.I. 'Cordtex') or by electrical initiation.

The higher the charge density the more effective the blasting will be under these conditions. In practice this means one big stick is better than the same amount of explosive in two small sticks. In the Seward Peninsula circa $\frac{1}{2}$ lb sticks were used and found satisfactory. In Scandinavia circa $\frac{1}{4}$ lb and 2 oz sticks were used and were much less satisfactory. The 2 oz sticks were most unsatisfactory, not least because of the difficulty of loading a large number of sticks at one point.

The problem of initiation is closely associated with the problem of safety. The requirements of producing a section mean that there will be large quantities of flyrock or ejected material. Since the charge used, depth of placement, nature of soil etc. are all variable the distance of travel of flyrock will also be very variable. It is therefore impossible to quote a safe distance,,but the experience of the present writer suggests 800 yards should be regarded as a bare minimum using charges similar to those quoted above. This is easily achieved when using powder burning fuse and detonating fuse ('Cordtex') but not when using electrical initiation. For electrical initiation some form of shelter is essential. Detonating fuse, plus a single detonator and powder burning fuse is much the best combination to use. It completely obviates the need to load charges with detonators into the ground since the single detonator can be attached and safety fuse can be attached to a length of detonating fuse ('Cordtex') above ground. A severe practical problem arose in both the Seward Peninsula and in Finnmark since detonating fuse was not available. Hence electrical detonation had to be used. A shelter is then essential and the only practical solution found was to use a 50 gallon oil drum with the top removed, laid horizontally pointing away from the blast, with an adequate cover of soil. A very high voltage wireless dry battery was used for initiation of a number of charges at 100 m distance. A better solution would be to take an appropriate electrical exploder into the field area (the transport of detonating fuse, especially by aircraft, is naturally controlled by stringent regulations and is therefore an expensive undertaking). The problem of a series of electrical detonators under difficult field conditions was one of the most difficult problems encountered. Special consideration should be given to this point before the field work starts since availability of explosives does not mean availability of sophisticated means of initiation.

When using powder burning fuses and detonators waterproofing of the joint between fuse and detonator is essential. A rubberised sealing compound of the type commonly used for vehicles was found to be satisfactory. Igniting powder burning fuse by simply holding a flame to a cut end is very unreliable. A much better means of initiation is by slitting the final ½ inch of the fuse longitudinally, laying the match against the powder core and closing the slit so that only part of the head protrudes. The appropriate match striker is then drawn across the match tip so that the fuse is reliably ignited with the initial striking of the match head.

Blasting is not as fast a means of excavation as might be thought. Up to three hours may be required to prepare a single round of explosives under difficult conditions (which are normal in the sub arctic). Several rounds are needed for most pits. Pits left overnight frequently become flooded and blasting by propagation is then the best, and often the only solution. A technique found to be very successful was to tie ½ lb sticks at 45 cm intervals on a string (see Plate 63). The 'chain' is then lowered along the length of the pit and anchored at the bottom of the pit underwater as well as possible. A further stick of explosive is then fitted with detonator and powder burning fuse (well water proofed), as a priming charge, tied to an appropriate piece of wood near to the end and pushed into the mud at the bottom of the pit, near the centre of the chain (taking care not to push the wood into the mud so far that there is any risk of damage to the priming charge). This system cleared water almost 1 m deep from the pit shown in figure 63, leaving the pit clear for further blasting.

"Blasting practice" (I.C.I. 1962) was found to be an invaluable source of technical information on general use of explosives. Livingstone and Murphy (1959) give very useful data for blasting frozen ground. The technical literature from the appropriate manufacturer should be obtained in advance as only information on the simplest blasting and safety precautions is likely to be available from a 'field' explosives supplier (and it may be in the wrong language).

APPENDIX H
LOCATIONS OF SITES STUDIED

TABLE H1 SITES IN ALASKA

Site Number	Latitude and Longitude	Remarks
A5 (N)*	64°33.5'N, 165°27'W	SW slopes of Banner Peak
A6 (N)	" "	" " " " "
B1 (S)	64°56'N, 164°57.5'W	N of E end of Salmon Lake
B2 (S)	64°56.5'N, 164°52'W	Salmon Lake End moraine - obvious broken ground on map
C1 (B)	65°9'N 164°47.5'W	West of Labaree Hill
C2,C3 C5 (B)	65°9'N 164°47'W	" " " "
C8 (B)	65°10'N 164°42'W	Labaree Hill
D2 (B)	65°16'N 164°47.5'W	Little Ptarmigan Creek
D5 (B)	65°19'N 164°42'W	Near Coffee Creek Landing Ground
E2 (B)	65°00.5'N 164°42'W	Golden Gate Hill - not named on map - S of Golden Gate Creek, Height 1099ft.
E3 (S)	65°0'N 164°42.5'W	SW of Golden Gate Hill, NE of Homestake Creek
E7 (S)	64°56.5'N 164°50'W	Between Grouse and Crater Creeks
F2 (B)	65°18'N 164°44'W	Coffee Creek/Wonder Gulch junction area
FM1 (B)	65°18.5'N 164°43.5'W	Dome Creek near to Coffee Creek
X31 (B)	65°01.5'N 164°43'W	North flank Golden Gate Hill - see E2
X33 (B)	65°1.5'N 164°43'W	" " " " " " "
X34 (B)	65°1.5'N 164°43'W	" " " " " " "
X4 (B)	65°02'N 164°42.5'W	" " " " " " "
- (B)	65°20'N 164°45'W	COFFEE CREEK
- (N)	64°26'N 165°0' W	CAPE NOME - ESE of Nome
- (N)	64°46'N 166°28' W	CAPE WOOLLEY - NW of Nome
- (B)	64°46.5'N 164°36'W	MIDNIGHT MOUNTAIN
- (T)	65°16'N 166°50'W	POINT SPENCER
ESA	64°16'N 146°9'W	Richardson Highway Mile 287.5 (referred Pewe 1965)
H1	63°6'N 145°39'W	Denali Highway Mile 5
T1	62°43'N 142°14'W	Taylor Highway(Tetlin Junction 35miles)
YAR	63°39'N 145°52'W	Yardang Site(Pewe 1965)
-	64°4'N 141° W	Patterns on Alaska/Yukon Border
-	62°10'N c144°30'W	Patterns on eskers near Maclaren River.

* Letter in brackets indicates map.
B = Bendeleben Sheet - Map 3 in the pocket.
N = Nome " - " 4 " " "
S = Solomon " " 5 " " "
T = Teller " " 6 " " "

TABLE H2 SITES IN THE BRITISH ISLES - East Anglian Sites first.

Site Name	Map Sheet	Grid Reference	Height(Ft)
Babraham	TL 55	510513	125
Cockley Cley Heath	TF 80	803059	150
Congham Heath	TF 72	742234	200
The Drove, Brettenham	TL 98	915840	110
Eriswell High Warren	TL 77	779798	125
Euston Park/Rushford Park	TL 97	912796	100
Euston Lime Quarry	TL 87	895775	125
Fakenham Spinney	TL 87	895772	125
Garboldisham	TM 08	006815	100
Grimes Graves	TL 89	810902	75
Grimston Heath	TF 72	755227	175
Icklingham	TL 77	772730	-
Ixworth Chalk Pit	TL 96	941692	100
Knettishall Heath	TL 98	946804	100
Lakenheath Warren	TL 78	783803	125
Risby Poor's Heath	TL 76	776678	150
Rushford Park	see Euston Park		
Swaffham Golf Course	TF 80	806068	150
Swaffham Heath	TF 70	779087	125
Thetford Golf Course	TL 88	838843	125
Thetford Heath	TL 88	848804	125
Weather Heath	TL 77	784778	175
Weeting Heath	TL 78	757885	75
Ballynalacken Castle, Lisdoonvarna, Co Clare, Eire, cryoturbation near,	$53^{o}7'N$ $9^{o}22'W$*		
Bessyboot Mountain, Cumberland	NY 21	258125	1,800
Blaydon Sand Pit,	NZ 16	154623	-
Holy Island, Northumberland	NU 14	125418	-
Robinson Mountain, Cumberland	NY 21	202168	2,400

* Large scale maps of Eire don't have a grid reference system. The site is 2½ miles north west of Lisdoonvarna, on the first major road bend overlooking Ballynalacken Castle.

TABLE H3 NORTHERN NORWAY

Site Number	Site Name	Latitude and Longitude	Height
07A*	Sundheim	69°1'N 18°29'E	40m
U4A	Sennelandet	70°10'N 23°44'E	330m
U5A	near Stangvatnet	69°42'N 23°35'E	510m
U5B	near Survatnet	69°41'N 23°36'E	530m
U5C	near Stangvatnet	69°42'N 23°35'E	510m
U5D	near Stangvatnet	69°41.5'N 23°35'E	530m
V3A	Nord-Raksavarre	70°27'N 24°42'E	220m
V3B	Nord-Raksavarre	70°28'N 24°49'E	180m
V3C	Billefjordfjell	70°19.5'N 25°2'E	210m
V3D	Kistrandfjell	70°28'N 25°11'E	270m
V4B	Ytre Garadak	70°15.5'N 25°4'E	0-30m
W1A	Magerøy	71°3'N 25°47'E	240m
W1B	Magerøy	71°4'N 25°47'E	180m
1734/IV/A	Kvaenangsfjellet	69°54'N 21°33.5'E	400m

* Sites were indexed by adding a letter to the 1:100,000 map sheet code. e.g. 07A = Site A on map sheet 07

U5D = Site D on map sheet U5

1734/IV is one of the new 1:50,000 maps.

IMPORTANT NOTE Latitude and Longitude given in this table are normal (based on Greenwich Meridian) figures. The longitudes given in Appendix C are in the 'East of Oslo' system used on the 1:100,000 sheets (Oslo is 10°43'22.5" East of Greenwich).

APPENDIX J

ABBREVIATED GLOSSARY

This abbreviated glossary is intended to give a brief indication of the meaning of words for readers not familiar with them, or not familiar with the usage in this thesis. The definitions given below are not strict definitions and are not intended to compete with the definitions of the same words by previous authors. Where a section reference is given a strict or at least fuller interpretation is given in the main text. The abbreviated definitions given here are certainly not intended to stand alone as full definitions.

ACTIVE LAYER - a layer of ground, overlying permafrost, that seasonally thaws. See section 3.1.

BURIED RIDGE FORM - used as a purely descriptive phrase and should not be taken as implying that there was a pre-existing ridge that has since been buried.

CENTRAL AREA of a pattern, as opposed to the marginal area. Definition is obvious in the case of equiforms and elongates. For stripes the 'central area' refers to the corresponding part of the pattern, when recognisable, even when the stripes are of indefinite length.

CENTRAL DYKE FORM - an especially large pseudopod in the centre of the buried ridge form of some patterns, that is particularly persistent up and down slope. See section B.122.

CLAY SHIFT - clay rich areas found in sand of some East Anglian areas. Often there is a marked clay shift layer near the interface between sand and chalky material. See section 5.4.

CONTIGUOUS - a proposed descriptive term for pattern grouping, used when patterns all impinge upon one another. See section 2.43.

CONTINUOUS PERMAFROST - see section 3.1.

CRYOSTATIC - "an adjective describing freezing induced hydrostatic phenomena" (Washburn 1956, p 842). See section 2.51.

DISCONTINUOUS PERMAFROST - see section 3.1.

DOWNFREEZING - freezing of ground from the surface downwards.

DOWNFREEZING FRONT - the limit of penetration of freezing temperatures which are advancing downwards.

ELONGATE - proposed term for patterns with marked elongation of the units, but not indefinite elongation. See section 2.43.

EQUIFORM - proposed term for patterns in which the units are not markedly elongated. See section 2.43. This term is intended to include all the forms described by Washburn (1956) as circles, nets and polygons.

FROST TABLE - the upper limit of frozen ground, or alternatively the lower limit of penetration of thaw, whether in seasonal or permanently frozen ground. See section 3.1.

GROUPED - a proposed descriptive term for pattern grouping to cover patterns which are intermediate between 'contiguous' and 'isolate'. See section 2.43.

HEATH - this term is used in this thesis following the usage of Hopkins and Sigafoos (1951), "'Heath', in the strict sense refers to members of the family Ericaceae, but the writers use the term to mean an assemblage of plants that includes Ledum palustre subsp. decumbens, Vaccinium uliginosum, V. vitis-idaea subsp. minus, and Empetrum nigrum." (p 53)
ICE LENSES (ice gneiss) - parallel or subparallel segregations of ice usually formed by the 'Taber' mechanism. These range in size from a millimetre or so up to several centimetres. In this study the term 'ice lens' should not be taken to mean very large masses of ground ice (Sharp 1942a) unless specially qualified. See also section 3.32.
INFILLED TROUGH FORM - a purely descriptive term - c.f. buried ridge form.
ISOLATE - a proposed descriptive term for pattern grouping where the patterns are widely spaced and appear to rarely, if ever, impinge upon one another. See section 2.43.
MARGINAL AREA - see 'central area'.
MEANDROID - proposed descriptive term for a pattern appearance on air photographs (or rarely on the ground) when the patterns are definitely recognisable though the pattern form category (equiform, elongate etc.) cannot be readily recognised. See plate 81 and figure 56.
PERMAFROST TABLE - "a more or less irregular surface which represents the upper limit of the permafrost" (Muller 1947, p 219).
PSEUDOPODS - see figure 28.
SOLIFLUCTION - this term is used as far as possible as originally proposed by Andersson (1906). See section 7.10.0.
SPORADIC PERMAFROST - see section 3.1.
STEP - see section 2.43
STRIPE - see section 2.43
TABER ICE - ice lenses which grow fed by water drawn through capillary sized pores i.e. by the mechanism investigated by Taber. See section 3.32.
THAW LAKE - lake originating, or considerably enlarged by, thawing and caving of the lake margins. See Hopkins 1949.
UPFREEZING - the penetration of freezing temperatures from below (by conduction of heat downwards into permafrost).
UPFREEZING FRONT - the upper limit of penetration of freezing temperatures penetrating from below.
ZELLENBODEN - miniature patterned ground. See Troll 1944.
ZERO CURTAIN - see section 3.2.

APPENDIX K

ARTIFACT FOUND IN THE GRIMES GRAVES SECTION

During the course of cleaning the section at Grimes Graves a flint with the appearance of an artifact was seen in the face. The flint was examined carefully in situ. It was adjacent to a small pseudopod deep in the sand chalk mixture of a buried ridge form. The conditions were ideal for identifying any post formational disturbance and there was absolutely no sign of this flint being a 'later addition'. After removal from the face the present writer doubted its human origin and hence did not record in exact detail the position of the find.

The artifact was examined by Dr. D Roe of the Institute of Archaeology, Oxford. The artifact is a "classic scraper made on a plain platform flake". This type of artifact can be found in a very wide range of cultures and hence cannot itself be used for dating purposes. There is only very faint patination on the artifact and there is some slight damage of the working edge since manufacture.

The position of the artifact leaves no doubt that the artifact was in place before active pattern development ceased and hence must be at least as old as the last permafrost phase in East Anglia. The latest possible date is thus late in the Weichsel Glaciation. The amount of patination on the artifact is similar to the patination on fractured faces of the large flints in the 'central dyke form'. These were presumably fractured during pattern development, possibly during the late stages of pattern development. This may suggest that the flint was incorporated in the pattern soon after manufacture and hence would suggest presence of man either very late in the Eemian Interglacial or during the Weichsel Glaciation. The amount of patination is remarkably slight if the flint is much older than this.

Another point that may be of archaeological interest is that patterning is present across the classic Grimes Graves site, and not 'boulder clay' as at present stated in archaeological accounts (e.g. Clarke 1963). This might or might not affect the interpretation of some of the archaeological evidence from this important site.

PERMAFROST MAP OF ALASKA

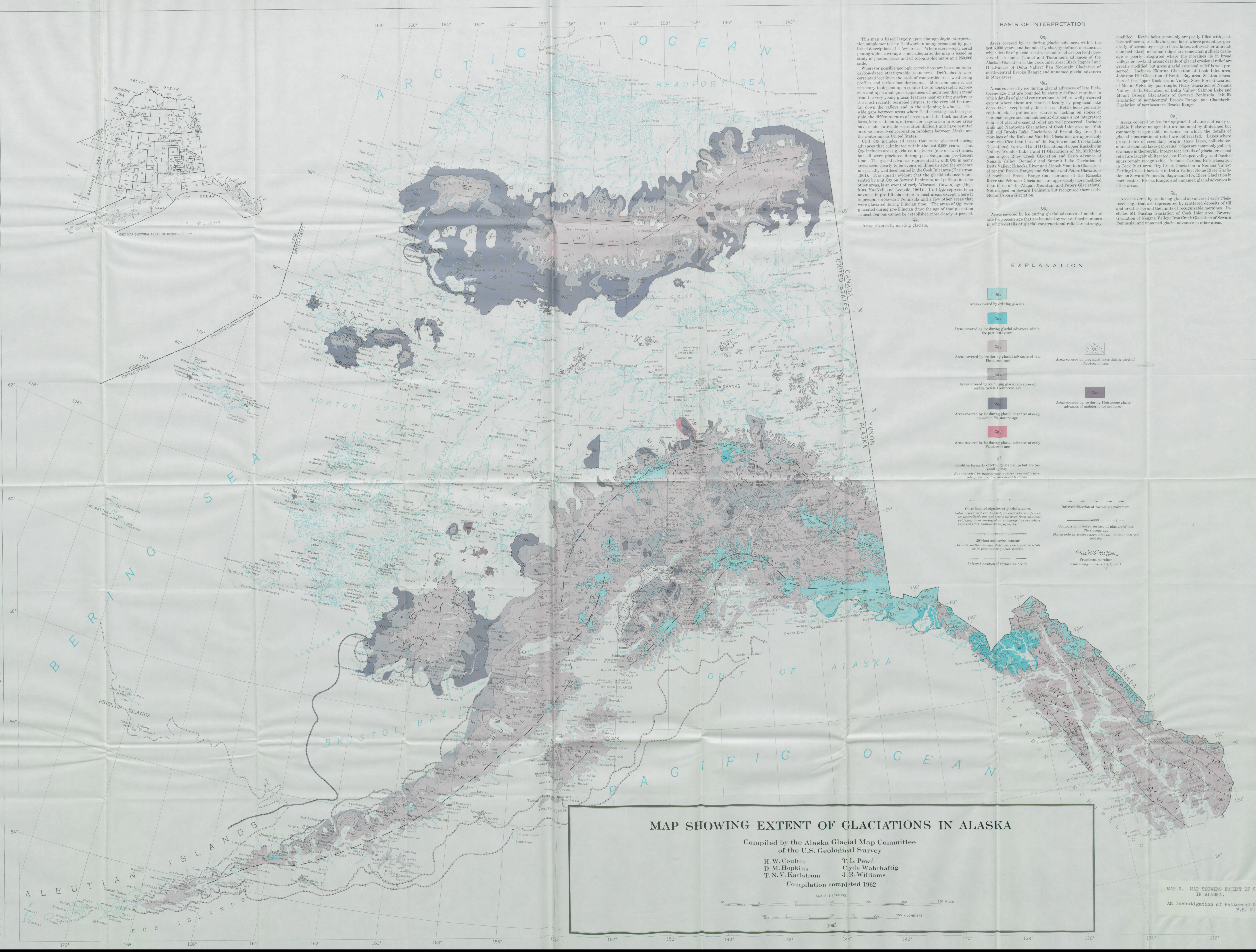
Compiled by
Oscar J. Ferrians, Jr.

SCALE 1:2 500 000

MAP 1. PERMAFROST MAP OF ALASKA.
An Investigation of Patterned Grou[nd]
F.H. Nichols[on]

AREAS OF RESPONSIBILITY AND SOURCES OF INFORMATION

AREA	COMPILER	SOURCE OF INFORMATION
1	Coulter, H. W.	Coulter, H. W., in Karlstrom and others, 1964, U.S. Geol. Survey Misc. Geol. Inv. Map I-357.
[illegible]	[illegible]	[illegible]



BASIS OF INTERPRETATION

This map is based largely upon photogeologic interpretation supplemented by fieldwork in many areas and by published descriptions of a few areas. Where stereoscopic aerial photographic coverage is not adequate, the map is based on study of photomosaics and of topographic maps at 1:250,000 scale.

Wherever possible geologic correlations are based on radiocarbon-dated stratigraphic sequences. Drift sheets were correlated locally on the basis of comparable soils, weathering profiles, and surface boulder counts. More commonly it was necessary to depend upon similarities of topographic expression and upon analogous sequences of moraines that extend from the very young glacial features near existing glaciers or the most recently occupied cirques, to the very old features far down the valleys and in the adjoining lowlands. The wide gaps between areas where field checking has been possible, the different rates of erosion, and the thick mantles of loess, lake sediments, outwash, or vegetation in some areas have made statewide correlation difficult and have resulted in some unresolved correlation problems between Alaska and the conterminous United States.

Unit Qg_5 includes all areas that were glaciated during advances that culminated within the last 6,000 years. Unit Qg_4 includes areas glaciated at diverse (one or two?) times, but all were glaciated during post-Sangamon, pre-Recent time. The glacial advances represented by unit Qg_3 in many areas seem clearly to be events of Illinoian age; the evidence is especially well documented in the Cook Inlet area (Karlstrom, 1961). It is equally evident that the glacial advance represented by unit Qg_3 on Seward Peninsula, and perhaps in some other areas, is an event of early Wisconsin (Iowan) age (Hopkins, MacNeil, and Leopold, 1961). Unit Qg_2 represents an advance in pre-Illinoian time in most areas, except where it is present on Seward Peninsula and a few other areas that were glaciated during Illinoian time. The areas of Qg_1 were glaciated during pre-Illinoian time; the age of that glaciation in most regions cannot be established more closely at present.

Qg_6

Areas covered by existing glaciers.

Qg_5

Areas covered by ice during glacial advances within the last 6,000 years, and bounded by sharply defined moraines in which details of glacial constructional relief are perfectly preserved. Includes Tunnel and Tustumena advances of the Alaskan Glaciation in the Cook Inlet area; Black Rapids I and II advances of Delta Valley; Fan Mountain Glaciation of north-central Brooks Range; and unnamed glacial advances in other areas.

Qg_4

Areas covered by ice during glacial advances of late Pleistocene age that are bounded by sharply defined moraines in which details of glacial constructional relief are well preserved except where mantled by younger proglacial lake deposits or exceptionally thick loess. Kettle holes generally contain lakes; gullies are scarce or lacking on slopes of morainal ridges and embankments; drainage is not integrated; details of glacial erosional relief are well preserved. Includes Knik and Naptowne Glaciations of Cook Inlet area; Mak Hill and Brooks Lake Glaciations of Bristol Bay area (but moraines of the Knik and Mak Hill Glaciations are appreciably more modified than those of the Naptowne and Brooks Lake Glaciations); Farewell I and II Glaciations of upper Kuskokwim Valley; Wonder Lake I and II Glaciations of Mt. McKinley quadrangle; Riley Creek Glaciation and Carlo advance of Nenana Valley; Donnelly and Summit Lake Glaciation of Delta Valley; Echooka River and Alapah Mountain Glaciations of central Brooks Range; and Schrader and Peters Glaciations of northeast Brooks Range (but moraines of the Echooka River and Schrader Glaciations are appreciably more modified than those of the Alapah Mountain and Peters Glaciations). Not mapped on Seward Peninsula but recognized there as the Mount Osborn Glaciation.

Qg_3

Areas covered by ice during glacial advances of middle or late Pleistocene age that are bounded by well-defined moraines in which details of glacial constructional relief are strongly modified. Kettle holes commonly are partly filled with peat, lake sediments, or colluvium, and lakes where present are generally of secondary origin (thaw lakes, colluvial- or alluvial-dammed lakes); morainal ridges are somewhat gullied; drainage is poorly integrated where the moraines lie in broad valleys or lowland areas; details of glacial erosional relief are greatly modified, but gross glacial erosional relief is well preserved. Includes Eklutna Glaciation of Cook Inlet area; Johnston Hill Glaciation of Bristol Bay area; Selatna Glaciation of the Upper Kuskokwim Valley; Slow Fork Glaciation of Mount McKinley quadrangle; Healy Glaciation of Nenana Valley; Delta Glaciation of Delta Valley; Salmon Lake and Mount Osborn Glaciations of Seward Peninsula; Itkillik Glaciation of northcentral Brooks Range; and Chamberlin Glaciation of northeastern Brooks Range.

Qg_2

Areas covered by ice during glacial advances of early or middle Pleistocene age that are bounded by ill-defined but commonly recognizable moraines on which the details of glacial constructional relief are obliterated. Lakes where present are of secondary origin (thaw lakes, colluvial-or-alluvial-dammed lakes); morainal ridges are commonly gullied; drainage is thoroughly integrated; details of glacial erosional relief are largely obliterated, but U-shaped valleys and faceted spurs remain recognizable. Includes Caribou Hills Glaciation in Cook Inlet area; Dry Creek Glaciation in Nenana Valley; Darling Creek Glaciation in Delta Valley; Nome River Glaciation on Seward Peninsula; Sagavanirktok River Glaciation in northeastern Brooks Range; and unnamed glacial advances in other areas.

Qg_1

Areas covered by ice during glacial advances of early Pleistocene age that are represented by scattered deposits of till and erratics beyond the limits of recognizable moraines. Includes Mt. Susitna Glaciation of Cook Inlet area; Browne Glaciation of Nenana Valley; Iron Creek Glaciation of Seward Peninsula; and unnamed glacial advances in other areas.

MAP SHOWING EXTENT OF GLACIATIONS IN ALASKA

Compiled by the Alaska Glacial Map Committee
of the U.S. Geological Survey

H. W. Coulter — T. L. Péwé
D. M. Hopkins — Clyde Wahrhaftig
T. N. V. Karlstrom — J. R. Williams

Compilation completed 1962

SCALE 1:2 500 000

1965

MAP 2. MAP SHOWING EXTENT OF GLACIATIONS IN ALASKA.

An Investigation of Patterned Ground - F.H. Nicholson.

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

BENDELEBEN

ALASKA
TOPOGRAPHIC SERIES
SECOND JUDICIAL DIVISION

INTERIOR—GEOLOGICAL SURVEY, WASHINGTON, D. C.—1956—N5
M R-2647

COMPILED, EDITED, AND PUBLISHED BY THE GEOLOGICAL SURVEY

CONTROL BY USGS, USC&GS, AND USCE

COMPILED IN 1955 FROM ARMY MAP SERVICE 1:50,000 SERIES MAPS 1952
AERIAL PHOTOGRAPHS TAKEN 1950

UNIVERSAL TRANSVERSE MERCATOR PROJECTION, ZONE 3
1927 NORTH AMERICAN DATUM

UNCHECKED ELEVATIONS ARE SHOWN IN BROWN AND BLUE

SCALE 1:250,000

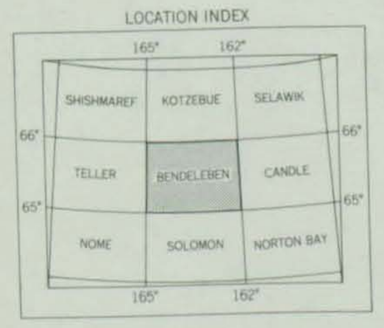
5 0 5 10 15 20 25 MILES

5 0 5 10 15 20 25 KILOMETERS

CONTOUR INTERVAL 200 FEET
DATUM IS MEAN SEA LEVEL

1955 MAGNETIC DECLINATION AT SOUTH EDGE OF SHEET VARIES FROM 18° TO 20° EAST
THIS MAP IS AVAILABLE IN BOTH SHADED RELIEF AND CONTOUR EDITIONS
FOR SALE BY U.S. GEOLOGICAL SURVEY
FAIRBANKS, ALASKA FEDERAL CENTER, DENVER, COLORADO WASHINGTON 25, D.C.
A FOLDER DESCRIBING TOPOGRAPHIC MAPS AND SYMBOLS IS AVAILABLE ON REQUEST

LOCATION INDEX



ROAD CLASSIFICATION

DRY WEATHER ROADS

IMPROVED DIRT ...

UNIMPROVED DIRT .

TRAILS ..

BENDELEBEN, ALASKA
N6500—W16200/60X180

1950

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

NOME

ALASKA
TOPOGRAPHIC SERIES
SECOND JUDICIAL DIVISION

COMPILED, EDITED, AND PUBLISHED BY THE GEOLOGICAL SURVEY

CONTROL BY USGS, USC&GS, AND USCE

HYDROGRAPHY COMPILED FROM USC&GS CHARTS 9380 AND 9383

COMPILED IN 1955 FROM ARMY MAP SERVICE 1:50,000 SERIES MAPS 1952
AERIAL PHOTOGRAPHS TAKEN 1950

UNIVERSAL TRANSVERSE MERCATOR PROJECTION, ZONE 3
1927 NORTH AMERICAN DATUM

RED TINT INDICATES AREA IN WHICH ONLY
LANDMARK BUILDINGS ARE SHOWN

UNCHECKED ELEVATIONS ARE SHOWN IN BROWN AND BLUE

SCALE 1:250000

5 0 5 10 15 20 25 MILES

5 0 5 10 15 20 25 KILOMETERS

CONTOUR INTERVAL 200 FEET
DOTTED LINES REPRESENT 100 FOOT CONTOURS
DATUM IS MEAN SEA LEVEL
DEPTH CURVES IN FEET—DATUM IS MEAN LOWER LOW WATER
SHORELINE SHOWN REPRESENTS THE APPROXIMATE LINE OF MEAN HIGH WATER
1955 MAGNETIC DECLINATION AT SOUTH EDGE OF SHEET VARIES FROM 15° TO 17° EAST

THIS MAP IS AVAILABLE IN BOTH SHADED RELIEF AND CONTOUR EDITIONS

FOR SALE BY U.S. GEOLOGICAL SURVEY
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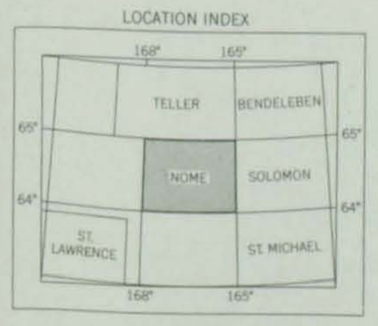
A FOLDER DESCRIBING TOPOGRAPHIC MAPS AND SYMBOLS IS AVAILABLE ON REQUEST

INTERIOR-GEOLOGICAL SURVEY, WASHINGTON, D. C.—1956
M R-1894

LOCATION INDEX



ROAD CLASSIFICATION

DRY WEATHER ROADS

IMPROVED DIRT . . . UNIMPROVED DIRT

TRAILS . . .

NOME, ALASKA
N6400—W16500/60X180

1950

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

SOLOMON

ALASKA
TOPOGRAPHIC SERIES
SECOND JUDICIAL DIVISION

COMPILED, EDITED, AND PUBLISHED BY THE GEOLOGICAL SURVEY

CONTROL BY USGS, USC&GS, AND USCE

HYDROGRAPHY COMPILED FROM USC&GS CHARTS 9380 AND 9382

COMPILED IN 1955 FROM ARMY MAP SERVICE 1:50,000 SERIES MAPS
1953 AND 1954 AERIAL PHOTOGRAPHS TAKEN 1950

UNIVERSAL TRANSVERSE MERCATOR PROJECTION, ZONE 3
1927 NORTH AMERICAN DATUM

UNCHECKED ELEVATIONS ARE SHOWN IN BROWN AND BLUE

SCALE 1:250000

5 0 5 10 15 20 25 MILES

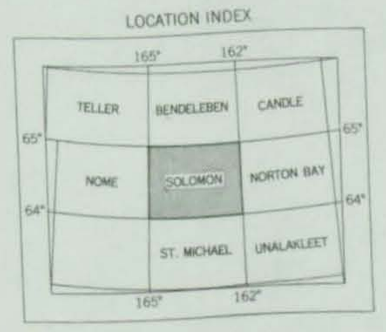
5 0 5 10 15 20 25 KILOMETERS

CONTOUR INTERVAL 200 FEET
DOTTED LINES REPRESENT 100 FOOT CONTOURS
DATUM IS MEAN SEA LEVEL
DEPTH CURVES IN FEET—DATUM IS MEAN LOWER LOW WATER
SHORELINE SHOWN REPRESENTS THE APPROXIMATE LINE OF MEAN HIGH WATER
1955 MAGNETIC DECLINATION AT SOUTH EDGE OF SHEET VARIES FROM 17°30' TO 19°30' EAST
THIS MAP IS AVAILABLE IN BOTH SHADED RELIEF AND CONTOUR EDITIONS

FOR SALE BY U.S. GEOLOGICAL SURVEY
FAIRBANKS, ALASKA FEDERAL CENTER, DENVER, COLORADO WASHINGTON 25, D.C.
A FOLDER DESCRIBING TOPOGRAPHIC MAPS AND SYMBOLS IS AVAILABLE ON REQUEST

INTERIOR—GEOLOGICAL SURVEY, WASHINGTON, D. C.—1956
M R.1896

LOCATION INDEX



ROAD CLASSIFICATION

DRY WEATHER ROADS

IMPROVED DIRT . . .

UNIMPROVED DIRT . . .

TRAILS . . .

SOLOMON, ALASKA

N6400—W16200/60X180

1950

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

TELLER

ALASKA
TOPOGRAPHIC SERIES
SECOND JUDICIAL DIVISION

COMPILED, EDITED, AND PUBLISHED BY THE GEOLOGICAL SURVEY
CONTROL BY USC&GS AND USCE
HYDROGRAPHY COMPILED FROM USC&GS CHARTS 9380 AND 9385, AND HYDROGRAPHIC SURVEYS 7836, 7837, 7838, 7840, 7845, AND 7849
COMPILED IN 1955 FROM ARMY MAP SERVICE 1:50,000 SERIES MAPS 1950. AERIAL PHOTOGRAPHS TAKEN 1950
UNIVERSAL TRANSVERSE MERCATOR PROJECTION, ZONES 2 AND 1927 NORTH AMERICAN DATUM
UNCHECKED ELEVATIONS ARE SHOWN IN BROWN AND BLUE

SCALE 1:250 000

5 0 5 10 15 20 25 MILES

5 0 5 10 15 20 25 KILOMETERS

CONTOUR INTERVAL 200 FEET
DOTTED LINES REPRESENT 100-FOOT CONTOURS
DATUM IS MEAN SEA LEVEL
DEPTH CURVES IN FEET—DATUM IS MEAN LOWER LOW WATER
SHORELINE SHOWN REPRESENTS THE APPROXIMATE LINE OF MEAN HIGH WATER
1955 MAGNETIC DECLINATION AT SOUTH EDGE OF SHEET VARIES FROM 14°30' TO 17°30' EAST
THIS MAP IS AVAILABLE IN BOTH SHADED RELIEF AND CONTOUR EDITIONS
FOR SALE BY U.S. GEOLOGICAL SURVEY
FAIRBANKS, ALASKA FEDERAL CENTER, DENVER, COLORADO WASHINGTON 25, D.C.
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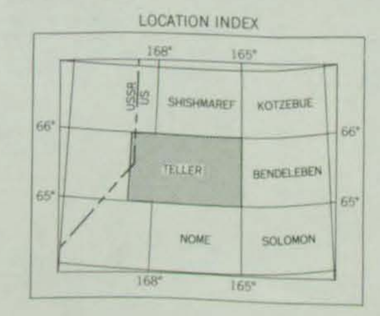
INTERIOR-GEOLOGICAL SURVEY, WASHINGTON, D. C.—1956
M R-2561

LOCATION INDEX



ROAD CLASSIFICATION
DRY WEATHER ROADS
IMPROVED DIRT
UNIMPROVED DIRT
TRAILS

TELLER, ALASKA
N6500—W16500/60X240
1950

EAST ANGLIA

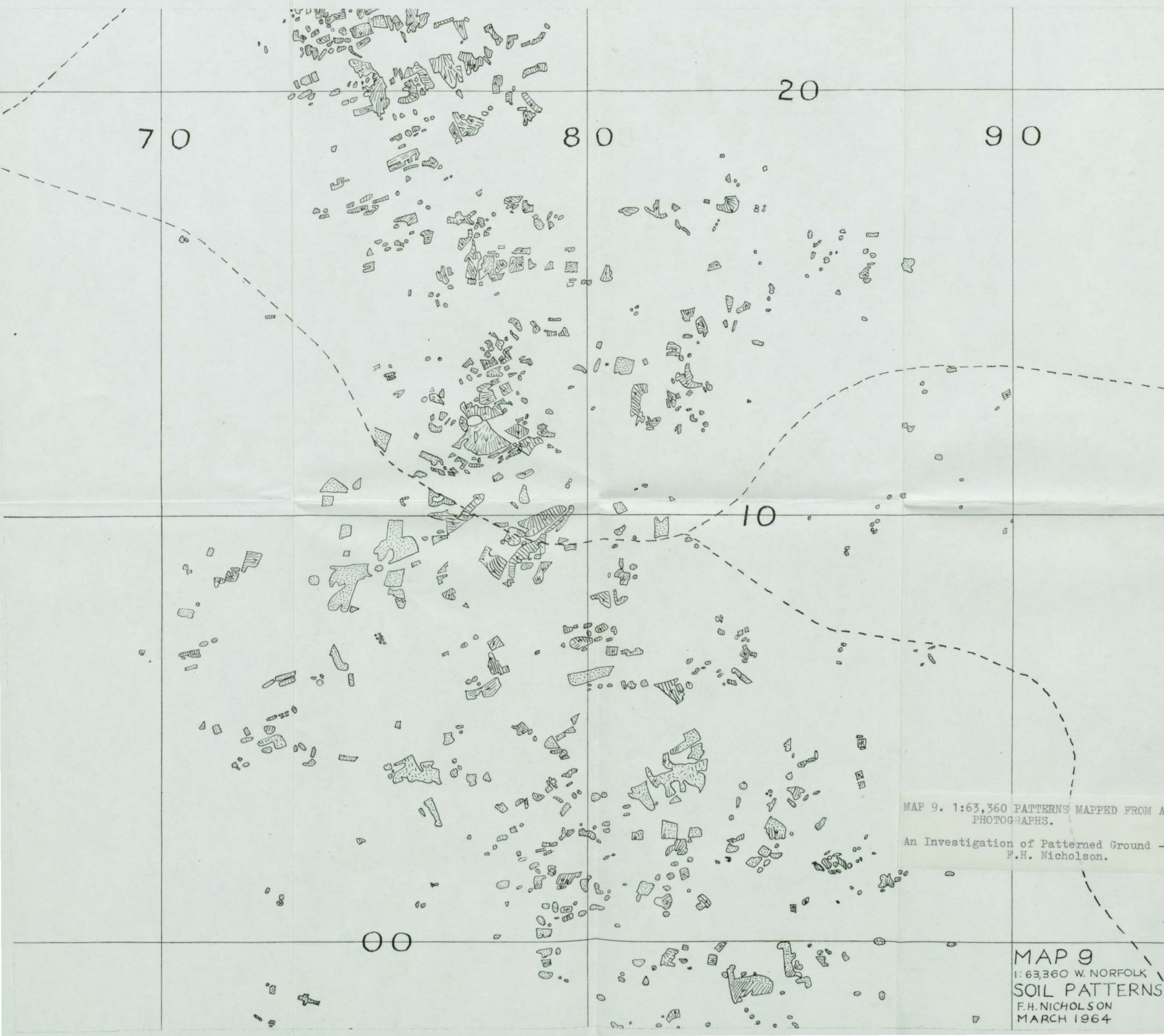
Scale: 1/250,000 or about Four Miles to One Inch

TO GIVE A GRID REFERENCE CORRECT TO ONE KILOMETRE

Made and published by the Director General of the ORDNANCE SURVEY, CHESSINGTON, SURREY, 1966

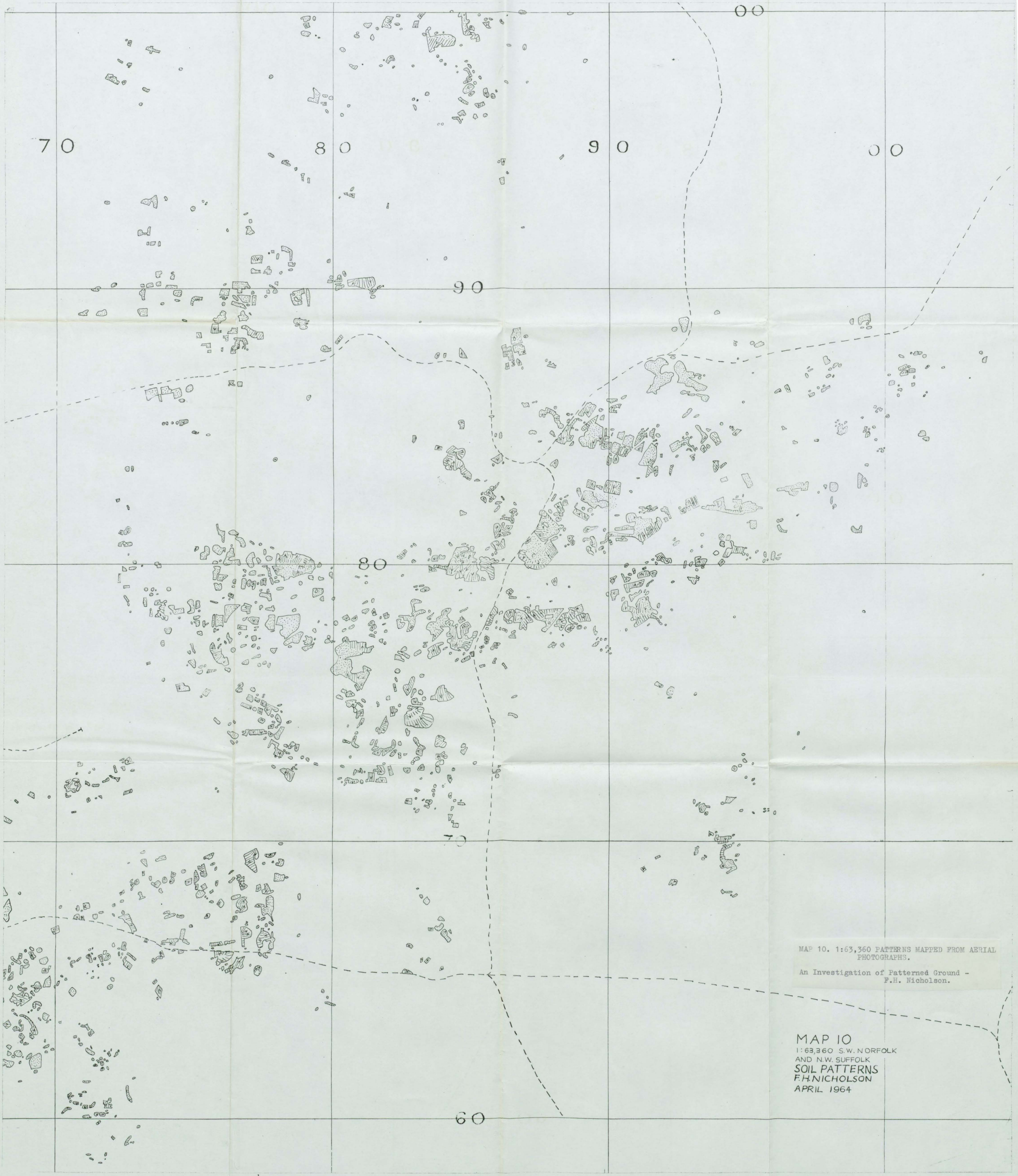
MAP 8. 1:63,360 PATTERNS MAPPED FROM AERIAL PHOTOGRAPHS.

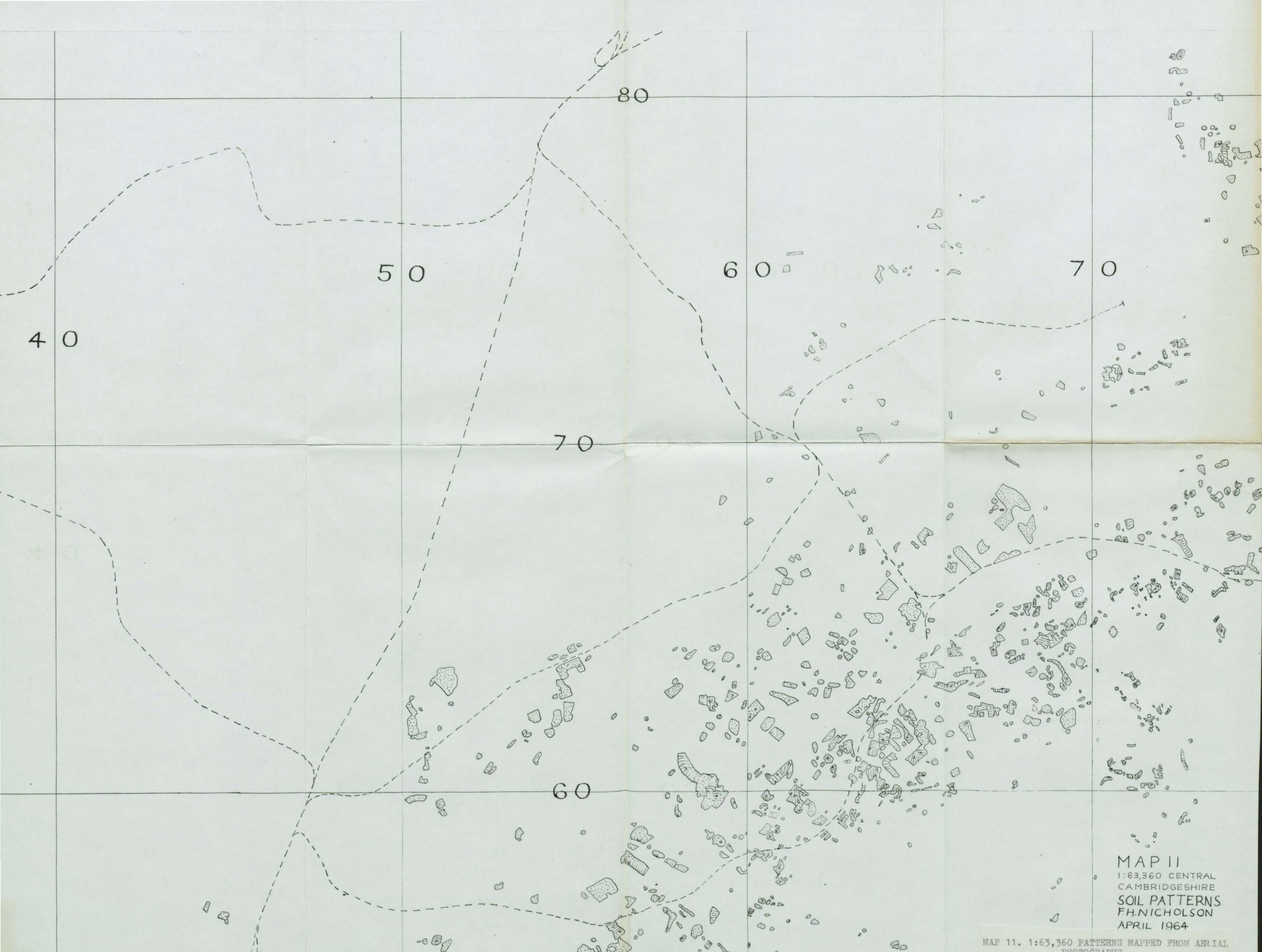
An Investigation of Patterned Ground - F.H. Nicholson.



MAP 9. 1:63,360 PATTERNS MAPPED FROM AERIAL PHOTOGRAPHS.

An Investigation of Patterned Ground - F.H. Nicholson.


00
70
80
90
00
90
80
70
60
MAP 10. 1:63,360 PATTERNS MAPPED FROM AERIAL PHOTOGRAPHS.
An Investigation of Patterned Ground - F.H. Nicholson.
MAP 10
1:63,360 S.W. NORFOLK
AND N.W. SUFFOLK
SOIL PATTERNS
F.H. NICHOLSON
APRIL 1964



MAP 11. 1:63,360 PATTERNS MAPPED FROM AERIAL PHOTOGRAPHS.

An Investigation of Patterned Ground - F.H. Nicholson.

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MAP 12. 1:63,360 PATTERNS MAPPED FROM AERIAL PHOTOGRAPHS.
An Investigation of Patterned Ground - F.H. Nicholson.
MAP 12
1:63,360 SOUTH CAMBRIDGESHIRE
SOIL PATTERNS
F.H. NICHOLSON
APRIL 1964

	TEGNFORKLARING	LEGEND	LÉGENDE	ZEICHENERKLÄRUNG
	Hovedvei, gjennomgangsvei	Main road, through route	Route de grande circulation	Hauptstrasse, Fernverkehrstrasse
	Annen riksvei	Other main road	Autre route nationale	Landeshauptstrasse
	Fylkesvei	Secondary road	Route provinciale	Provinzstrasse
	Kommunal eller privat vei	Local or private road	Route communale ou privée	Gemeinde- oder Privatstrasse
	Vei under anlegg	Road under construction	Route en construction	Strasse im Bau
	Fast veidekke. Asfalt, betong	Metalled road. Asphalt, concrete	Route revêtue. Asphalte, beton	Fester Strassenbelag. Asphalt, Beton
	Fast veidekke. Oljegrus	Metalled road. Oil-gravelled	Route revêtue. Gravier imprégnie	Fester Strassenbelag. Ölkies
E6 20	Veinummer	Road number	Numéro de route	Strassennummer
3	Avstander i km	Distance in km.	Distances en km	Entfernungen in km
17	Stengt i vintersesongen	Closed in the winter season	Fermé en hiver	Im Winter gesperrt
	Bomvei. Avgift	Toll road	Route à péage	Strasse, gebührenpflichtig
	Sperret for alminnelig trafikk	Closed to the public	Voie privée	Strasse für allgemeinen Verkehr gesperrt
	Sti, kjerrevei	Footpath, track	Sentier, route carrossable	Fussweg, befahrbarer Weg
	Vardet sti, båtrute på innsjö	Marked footpath, boat connection on lake	Sentier soigné, service de bateau sur lac	Markierter Fussweg, Binnenschiffsverbindung
	Rute uten tydelig sti eller varder, båtmulighet. Hvor rutene går over breer, er tau og förer nödvendig	Unmarked footpath. Where the path crosses a glacier rope and guide are necessary	Sentier non indiqué et sans gué bateau à louer. Corde et guide nécessaires où la piste traverse glacier	Weg ohne deutliche Markierung, Bootsverbindung. Bei Wegführung über Gletscher sind Seil und Führer notwendig
	Jernbane med stasjon og stoppested	Railway with station and halt	Chemin de fer avec gare et halte	Eisenbahn mit Bahnhof und Haltestelle
	Jernbanetunnel	Railway tunnel	Tunnel ferroviaire	Eisenbahntunnel
	Ferjerute	Car ferry	Bac	Fähre
	Skipsrute	Shipping route	Ligne maritime	Schiffslinie
19	Foss med fallhöyde i meter	Waterfall with height in metres	Chute d'eau avec hauteur en mètres	Wasserfall mit Fallhöhe in Metern
BERGEN	By med mer enn 15 000 innbyggere	Town with more than 15,000 inhabitants	Ville de plus de 15 000 habitants	Stadt mit mehr als 15 000 Einwohnern
Larvik	By eller tettsted med 2 000—15 000 innbyggere	Built-up area with 2,000—15,000 inhabitants	Ville ou localité de 2 000—15 000 habitants	Stadt oder Ortschaft mit 2 000—15 000 Einwohnern
Stavern	By eller tettsted med 200—2 000 innbyggere	Built-up area with 200—2,000 inhabitants	Ville ou localité de 200—2 000 habitants	Stadt oder Ortschaft mit 200—2 000 Einwohnern
	Mindre hussamling, poststed, gård, seter o.l.	Hamlet, postplace, farm, seter etc.	Petite localité, poste, ferme, châlet etc.	Kleinere Hausansammlung, Poststelle, Hof, Gut o.ä.
	Kirke, kapell	Church, chapel	Eglise, chapelle	Kirche, Kapelle
	Tollstasjon	Customs station	Douane	Zollstation
	Ekserserplass	Army camp	Champ de manoeuvres	Garnison
	Gruve	Mine	Mine	Bergwerk
	Fyr	Lighthouse	Phare	Leuchtfeuer
	Flyplass, sjöflyhavn	Airport	Aéroport	Flugplatz
364	Höyde over havet i meter	Height above sea-level in metres	Altitude en mètres	Höhe über dem Meeresspiegel in Metern
	Veiens höyeste punkt i meter	Highest point of the road in metres	L'endroit le plus elevé de la route en mètres	Der höchste Punkt der Strasse in Metern
	Dybde i meter	Depth in metres	Profondeur en mètres	Tiefe in Metern
	Turist- eller höyfjellshotell	Country- or mountain-hotel (top grade)	Hôtel de tourisme ou de haute montagne	Turisten- oder Gebirgshotel
	Flere turist- eller höyfjellshoteller på samme sted	More than one country- or mountain-hotel at the same place	Plusieurs hôtels de tourisme ou de haute montagne dans le même lieu	Mehrere Turisten- oder Gebirgshotels am gleichen Ort
	Hotell, gjestgiveri, pensjonat	Hotel, guest house, boarding house	Hôtel, auberge, pension	Hotel, Gasthaus, Pension
	Flere hoteller, gjestgiverier, pensjonater på samme sted	More than one hotel, guest house, boarding house at the same place	Plusieurs hôtels, auberges, pensions dans le même lieu	Mehrere Hotels, Gasthäuser, Pensionen am gleichen Ort
	Turisthytte. Betjent	Tourist hut—with service	Auberge de montagne	Turistenhütte—mit Bedienung
	Turisthytte. Selvbetjent	Tourist hut—with self-service	Refuge	Turistenhütte — mit Selbstbedienung
D.N.T.	Turisthytte tilhörende Den Norske Turistforening eller hytter der DNTs medlemmer har fortrinnsrett. De övrige turistforeningers forkortelser — se nedenfor	Tourist hut belonging to the Norwegian Touring Club (DNT) or hut where members of DNT have priority. For abbreviation of other tourist associations—see below	Châlet de l'organisation de Tourisme en Norvège, (DNT), ou refuge avec droit de préséance pour les membres de DNT. Abréviation des noms des autres organisations de tourisme — voir ci-dessous	Turistenhütte, der Norwegischen Fremdenverkehrsvereinigung (DNT) zugehörend oder mit Vorzugsrecht für Mitglieder der DNT. Abkürzungen weiterer Vereinigungen —siehe unten
	Spesielt velordnet campingplass	Camping site—first class	Terrain de camping de première classe	Erstklassiger Zeltplatz
	Campingplass med sanitæranlegg	Camping site with sanitary facilities	Terrain de camping avec installation sanitaire	Zeltplatz mit sanitären Anlagen
	Annen godkjent campingplass	Other approved camping site	Autre terrain de camping approvè	Anderer geprüfter Zeltplatz
	Campingplass med hytter og sanitæranlegg	Camping site with huts and sanitary facilities	Terrain de camping avec cabines et installation sanitaire	Zeltplatz mit Hütten und sanitären Anlagen
	Annen godkjent campingplass med hytter	Other approved camping site with huts	Autre terrain de camping approvè avec cabines	Anderer geprüfter Zeltplatz mit Hütten
M	Motell	Motel	Mōtel	Motel
	Ungdomsherberge	Youth hostel	Auberge de jeunesse	Jugendherberge
	Særlig vakkert utsiktspunkt	Exceptionally beautiful view	Trés joli point de vue	Besonders schöner Aussichtspunkt
	Fuglefjell	Bird colony	Colonie d'oiseaux	Vogelberg
	Ruin, minnesmerke	Ruin, monument	Ruines, monument	Ruine, Denkmal
	Annen severdighet	Other interesting place	Autre curiosité	Andere Sehenswürdigkeit
B	Friluftsbad	Open air bath	Piscine de plein air	Freiluftsbad
	Skiheis, skitrekk	Skilift	Téléphérique et télésiège	Skilift
P	Parkeringsplass	Car park	Lieu de stationnement	Parkplatz
	Hovedsakelig skog	Predominantly forest	Forêt dominante	Vorwiegend Wald
	Bre	Glacier	Glacier	Gletscher
	Urent farvann	Shoals	Hauts-fonds	Flaches Fahrwasser, Brandung
	Fyrsektorer for kystfyr. Særlig smale sektorer er av tekniske grunner alltid avmerket hvite	Sectors of coastal lighthouse beam. Extremely small sectors are for technical reasons shown in white	Secteurs balayés par des phars. Des secteurs très étroits sont pour raisons techniques, toujours marqués en blanc	Leuchtsektoren für Küstenleuchtfeuer. Besonders schmale Sektoren sind aus technischen Gründen immer weiss gehalten
	Riksgrense	International boundary	Frontière	Staatsgrenze
	Fylkesgrense	County boundary	Limite departementale	Provinzgrenze
	Snowmobilrute	Snowmobile route	Autochenille	Schneeraupen-Strecke

Turistforeninger: D. N. T. = DEN NORSKE TURISTFORENING
N.O.T. = Narvik og Omegn Turistforening. T.O.T. = Tromsø og Omegn Turistforening.

Bomveier: Ved to forskjellige symboler gis opplysninger om veier som er belagt med avgift og veier som er helt sperret for alminnelig trafikk (skogsbilveier). Vi gjør oppmerksom på at disse forhold stadig forandres og at redaksjonen er takknemlig for korrigeringer. Vær også oppmerksom på at skilt med «All trafikk forbudt» e. l. må oppfattes som om det var bom. På kartet er derfor slike skilt markert som sperret vei.

Vintersperrede veier: Alle riksveier og viktigere fylkesveier som er sperret i vintersesongen (dvs. i regelen i tiden november—mai), er markert på kartet med røde flagg. Vær imidlertid oppmerksom på at mange bygdeveier og private veier (hvite veier) også er sperret for trafikk om vinteren uten at dette er markert på kartet. Dette gjelder særlig seterveier og mindre veier i ubebodde strøk.

MAGERØYA
Nordkapp
PORSANGER
HALVØYA
PORSANGEN
SVÆRHOLT
HALVØYA
NORDKINN
HALVØYA
VARANGER
HALVØYA
VARANGERFJORDEN
ØSTHAVET
KEVO
NASJONALPARK
LEMMENJOKI
NASJONALPARK
INARI
(ENARE)
SKOGERØYA